TOWARDS WASTEWATER BIOREFINERIES: INTEGRATED BIOREACTOR AND PROCESS DESIGN FOR COMBINED WATER TREATMENT AND RESOURCE PRODUCTIVITY

Report to the

Water Research Commission

by

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EXECUTIVE SUMMARY

In this project, we investigated the wastewater biorefinery (WWBR) concept: the integrated processing of a wastewater stream or streams to generate products of value, including "clean" water, and remediate the effluent simultaneously. In this approach, products of variable value are produced concomitantly with clean water as a product, typically through multiple unit operations. The preference is to generate products of sufficient value to make the biorefinery economically viable. Our focus has been on developing and testing this concept, as well as evaluating its applicability to and potential in the South African context.

We are at a time in our anthropological history where both water and waste are being considered in new ways. A strong focus is in place to reuse resources through industrial metabolism and circular economy. Projects envisioning water and waste together are beginning to emerge in Europe. The overview in this project shows that South Africa has equivalent possibilities. However, implementation of these potential projects is difficult because maintaining the integrity of the basic water treatment infrastructure and its optimal performance is already a struggle in South Africa with its burgeoning urban populations and limited financial and skill-based resources. By integrating the goals of water treatment with the goals of the bioeconomy, there is great potential to transcend these challenges and create a new industry.

In this project, we review the relevant research done both internationally and nationally. We present extensive literature reviews on the different aspects of WWBR. We investigate specific aspects through interviews with industry stakeholders. This is followed by a review on the wastewater streams available in South Africa. We examine some potential products and the bioreactors required to produce them. We begin to examine some of our findings on bioreactors and products through laboratory studies. To contextualise the findings in an integrated system, a generic flowsheet and mass balance model is developed. We explore the features of the integrated biorefinery using this model to assess a few conceptual case studies.

The application of WWBRs does not generally need new technologies, but rather the integration and optimisation of existing technologies for multiple benefits. Throughout this work, it is evident that there are both perceptual and practical hurdles to implement WWBRs. These hurdles include risk aversion, policy constraints and lagging technological adaptions. This represents a constraint in the development of WWBR. Thus, sociological intervention is needed alongside the technological advances.

There is increased cooperation between academia, state entities and industry on specific technologies – to a greater extent internationally, but also increasingly so in South Africa. This is a critical requirement for implementing improved resource utilisation and the combined approach to value addition and water treatment, and it needs to be nurtured. Significant focused work has been done globally and in South Africa on wastewater treatment and beneficiation using specific isolated technologies, but very little work has been done on integrating these into overall solutions.

Producing products more valuable than energy products is required for the WWBR to be economically feasible, with the conventional bioenergy products produced from residual organics. This requires changing the mindset about investment, risk and associated returns, identifying the relevant product range, and comparing conventional processing routes and what is possible from the wastewater. Waste may need to be reclassified to be used as a raw material.

The products listed in this report represent a fairly intensive overview of the products possible from the heterotrophic bacterial bioreactor, but the products possible from the algal, macrophyte and solids bioreactors have not been reviewed extensively. We identify that function-based products specific to niche industries, particularly those from which wastewater comes, are of substantive interest owing to their streamlined market uptake. These products may be peculiar to those industries. They depend on both the composition of the wastewater in that industry complex and the needs of the market surrounding it. There is a tension between producing "drop-in" products with an existing market and

novel function-based products with commodity uses in niche industries closely associated with the industry producing the wastewater. Biopolymers are particularly promising. We feel that even globally, the spectrum of potential products has not been completely investigated. A better overview can only be obtained through focused case studies, including integrated industry pilots coupled with market engagement.

Not all products can be produced in a non-sterile dilute environment. Ecological selection through bioreactor design and operation is a suitable way to direct productivity given the large, dilute volumes of substrate. These products may have the stigma of “waste”, which could limit their application in some areas. For example, wastewaters from food-related industries need to be considered to produce other than food-based products. This still allows reasonable possibilities for application in associated industries.

Wastewaters are characterised in this report according to volume, concentration and complexity. Complexity introduces the most uncertainty, which includes changing unpredictably over time. Appropriate bioreactor design is required to accommodate this uncertainty. Volume and concentration can be used in combination to determine the potential of the source. Superimposing regional location onto this data assists with identifying wastewater resources with potential as raw material feedstock.

This project has highlighted the need for WWBR bioreactors to function in variable, dilute environments, without the need for sterilisation. The requirements for bioreactors for WWBR are defined both from a design and operational perspective. The bioreactor has to contribute to providing an environment favouring the product of interest. Decoupling hydraulic and solid residence time is required, as is the need to create an ecological niche for self-selection of the desired microbial community. Enabling effective product recovery should be included as a design feature. Some existing bioreactor designs are suitable and should be studied in an integrated system, which should be coupled with product recovery.

Laboratory-scale studies are valuable in providing proof of concept regarding product generation from specific wastewater streams with concomitant delivery of compliant water. Some existing wastewater treatment works may easily be retrofitted to contribute to WWBR due to their location, their choice of reactor systems, or their willingness to experiment. These works should be investigated on a pilot scale. Industry champions need to perform pilot-scale experiments using real situations commonly encountered on plants. Laboratory-scale investigations of critical parameters such as aeration need to be pursued through scaled-down studies in the context of the WWBR.

There are a variety of downstream processing (DSP) options available that are well developed, but these have been employed in different situations than WWBR. These processes, including product recovery, need to be investigated further in the context of WWBR. This includes learning from industries such as the mineral industry, which also deals with dilute complex material. DSP options that fully exploit the benefits of retained biomass and decoupled production hold particular promise. These need to be explored in conjunction with the bioreactor designs.

The need to integrate multiple unit operations to ensure compliant water and the production of bioproduct/s is key. The four groupings of unit operations considered in this project were chosen because they each contribute to the functioning of the WWBR as a system. The heterotrophic microbial bioreactor, of which the bacterial biocatalyst is used as a representative example, is helpful to remove a high proportion of the organic carbon. Heterotrophic microbial systems are known for producing a wide range of commodity products with market potential. The photo-mixotrophic bioreactor represented by the algal bioreactor is present to scavenge high proportions of nutrients, particularly nitrogen and phosphorus. These systems are also known to produce commodity products. The macrophyte bioreactor targets the polishing of the exiting stream in terms of nitrogen, phosphorus and particulates to ensure compliant “fit for purpose” water as a product, with a macrophyte-based by-product. The solids bioreactor is a new perspective on beneficiation of bioslurries and the solid phases recovered during WWBR operation, generating products of value including biosolids.

In this project, these unit operations are integrated into a single system generating material inventories across the system. This can be used to evaluate possible scenarios in an integrated context by using generic flowsheet and mass balances. We demonstrate that integrative studies of the unit operations are critical. In the same way as we have developed criteria for the bioreactor design, we need to develop criteria for the functionalities required from the complete set of unit operations included and an understanding of their interactions. This is difficult to do for a general case and rather requires specific case studies.

Consistent data on wastewater is not available. This is the clearest need emerging from this study in terms of assessing the national position, both to develop the WWBR and for conventional environmental management. There is a need for specification of the approach to data collection, including the manner of measurement, frequency of recording and responsibility for reporting and collection. The data and the form required must be specified, which includes the development of appropriate instrumentation.

The economic considerations around specific WWBR cases cannot be considered in a generic manner, yielding a universal solution, but is dependent on regional locality, product market needs, logistics and other factors at play. A lack of sufficient data to inform economic decisions is an expected concern at this stage. Detailed techno-economic studies coupled with integrated pilot studies need to be performed on a case study basis to provide additional insight.

To further the progress of integrated systems, we need to harness the expertise of different disciplines, including anthropologists (who understand how new paradigms are adopted), policymakers, lawyers and economists, as well as people who can deal with multiple disciplines in an integrative way to build bridges. The Future Water Institute has been established at the University of Cape Town to achieve this.

Over the duration of this project, WWBRs have been developed from a nascent concept to a groundswell exciting many different groups. It has been a privilege to be a part of the journey.

NAVIGATING THIS REPORT

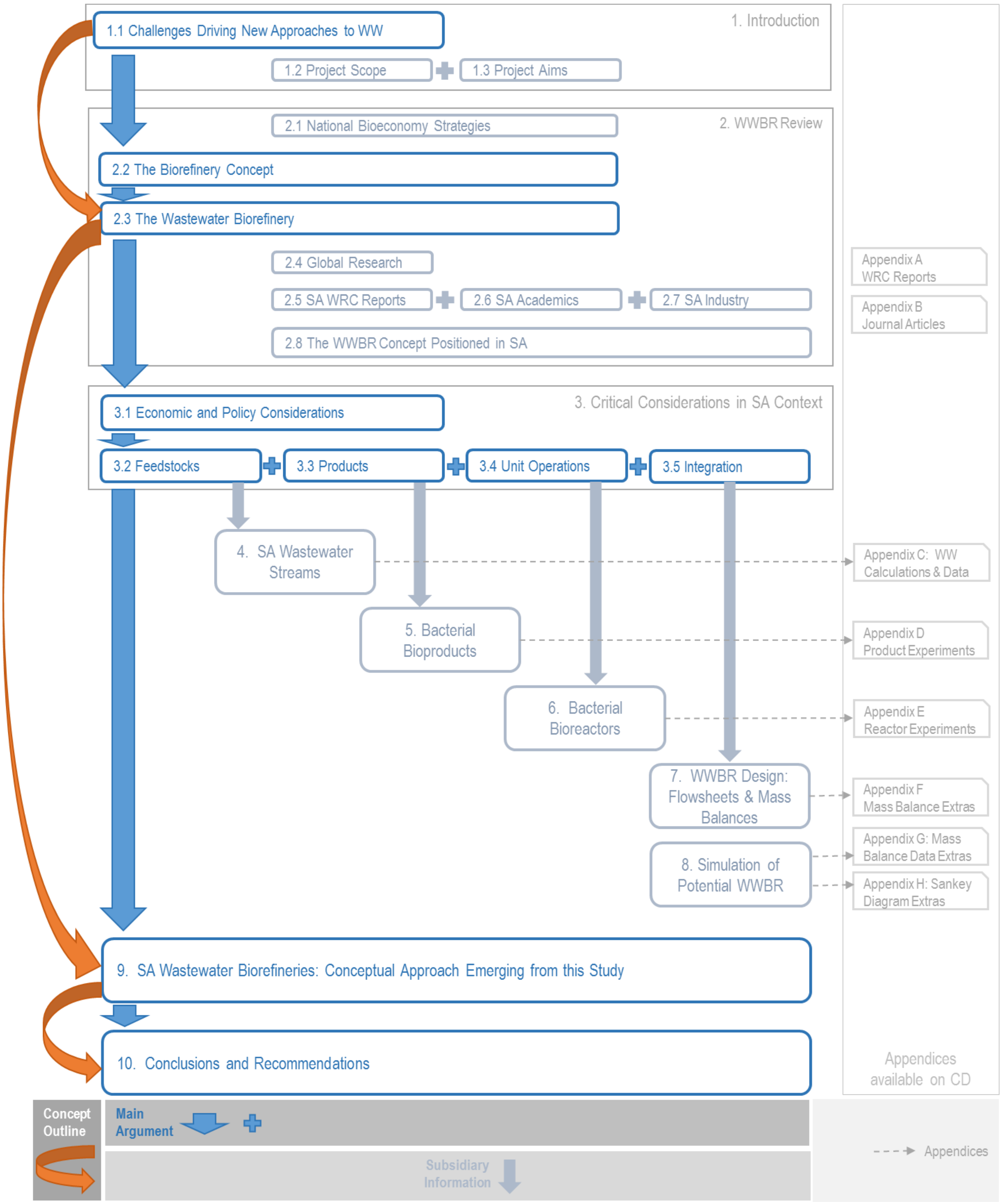

Figure i: Navigating the report "Towards Wastewater Biorefineries"

This project is a relatively comprehensive review of an emerging concept. As such, the report is designed as a document that can be used at multiple levels for different purposes. For a policymaker coming to the idea fresh from a more traditional space, using the introductory sections preparatory to reading the concluding chapters will provide a conceptual outline (curved orange arrows, extreme left in Figure i).

For a decision-maker wanting to explore this concept to possibly apply, the main argument should be followed more fully, including the critical considerations for the South African context (thick blue arrows in Figure i). In the event of the need to examine one or more aspects of the WWBR more carefully, the relevant detailed chapter can then be used (medium-width blue-grey arrows in Figure i).

For the researcher wishing to place the study within the flow of the development of the concept, the other parts of Chapter 1 (the Introduction) and Chapter 2 (the WWBR Review) will be helpful.

Finally, anyone wishing to take up the challenge of further research and implementation of the WWBR concept will find supplementary details in the appendices helpful (thin light-grey dashed arrows to right-hand block in Figure i). The appendices are available on CD.

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ACRONYMS AND ABBREVIATIONS

Abbreviation	Definition
AGS-SBR	Aerobic Granular Sludge in a Sequencing Batch Reactor
AGSR	Aerobic Granular Sludge Reactor
AOX	Adsorbable Organic Halogen
ASSAf	Academy of Science of South Africa
BNR	Biological Nutrient Removal
BOD	Biological Oxygen Demand
BOT	Build-Operate-Transfer
Capex	Capital Expenditure
CDP	Carbon Disclosure Project
CDW	Cell Dry Weight
CeBER	Centre for Bioprocess Engineering
COD	Chemical Oxygen Demand
CPUT	Cape Peninsula University of Technology
CSTR	Continuous Stirred Tank Reactor
DAFF	Department of Agriculture, Fisheries and Forestry (South Africa)
DMT	N,N-dimethyltryptamine
DSP	Downstream Processing
DST	Department of Science and Technology, South Africa
DUT	Durban University of Technology
DWA	Department of Water Affairs, South Africa (to 2013)
DWAF	Department of Water Affairs and Forestry, South Africa (to 2009)
DWS	Department of Water and Sanitation, South Africa (present)
EBRU	Environmental Biotechnology Rhodes University
FBBR	Fluidised Bed Biological Reactor
FOG	Fat, Oil and Grease
GHG	Greenhouse gases
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit
HRAP	High-rate Algal Ponds
HRT	Hydraulic Retention Time
IEA	International Energy Agency
IfBB	Institute for Bioplastics and Biocomposites (University of Applied Sciences and Arts Hannover, Germany)
INRA	Institute for Agricultural Research (France)
IWA	International Water Association
IWARR	IWA Resource Recovery Conference

Abbreviation	Definition
IWR	Institute for Water Research
IWWT	Institute for Water and Wastewater Technology
LCA	Life Cycle Analysis
LCI	Life Cycle Inventory
LLE	Liquid-Liquid Extraction
MBBR	Moving Bed Biofilm Reactor
MBR	Membrane Bioreactor
MSW	Municipal Solid Waste
NatSurv	National Industrial Water and Wastewater Survey
nl	not listed
NWRS	National Water Resource Strategy, South Africa
Opex	Operating and Maintenance Costs
PBR	Packed Bed Reactor
PE	Polyethylene
PGA	Polyglutamic Acid
PHA	Polyhydroxyalkanoate
PhaP	Putative HLA-DR-Associated Protein
PHB	Polyhydroxybutyrate
PLA	Polylactic Acid
PST	Primary Settling Tank
Q	Volumetric Flow Rate
R&D	Research and Development
RBC	Rotating Biological Contactor
RDI	Research, Development, and Innovation
RECORD	Renewable Energy Centre of Research and Development
RRB	International Conference on Renewable Resources and Biorefineries
SABIA	South African Biogas Industry Association
SALGA	South African Local Government Association
SANEDI	South African National Energy Development Institute
SAPIA	South African Petroleum Industry Association
SAPREF	South African Petroleum Refineries
SBR	Sequencing Batch Reactor
SC	Solids Content (mass of solids (dry mass) in sludge/mass of sludge)
SEV	Specific Effluent Volume
SIIT	Sirindhorn International Institute of Technology
SOL	Soluble Organic Loading
SS	Suspended Solids

Abbreviation	Definition
SSF	(Bio)Solid Substrate Fermentation
SWOT	Strength, Weakness, Opportunity and Threat
SWPN	Strategic Water Partners Network
TBR	Trickle Bed Reactor
TC	Total Carbon
TF	Trickling Filter
THL	Total Hydraulic Load
TKN	Total Kjehldahl Nitrogen
TN	Total Nitrogen
TOC	Total Organic Carbon
TOL	Total Organic Load
TP	Total Phosphorus
TSS	Total Suspended Solids
TU Delft	Delft University of Technology
UASB	Upflow Anaerobic Sludge Blanket
UCEWQ	Unilever Centre for Environmental Water Quality
UCT	University of Cape Town
UKZN	University of KwaZulu-Natal
USA	United States of America
UV	Ultraviolet
VFA	Volatile Fatty Acid
VOC	Volatile Organic Compound
VSS	Volatile Settleable Solid
WEF	Water Environment Federation, United States of America
WISA	Water Institute of Southern Africa
WRC	Water Research Commission, South Africa
wrcu	The number of non-bovine species equivalent to one bovine cattle unit in terms of water usage during processing
WWBR	Wastewater Biorefinery
WWTW	Wastewater Treatment Works

GLOSSARY OF TERMS

Beneficiation	Concentration or enrichment of a valuable product from its raw material
Biobased chemicals	Substitutes for petrochemicals or novel products derived from renewable biomass sources (recently fixed CO_2)
Biobased economy	An economy that integrates the full range of natural and renewable biological resources and the processing and consumption of these bioresources The biobased economy encompasses agriculture, forestry, fisheries, food and industrial sectors. It makes more use of biomass to replace fossil-based resources using biotechnology to produce fine chemicals and pharmaceuticals
Biobased products	Non-food products derived from biomass (plants, algae, crops, trees, marine organisms and biological waste from households, animals and food production) May range from high value-added fine chemicals such as pharmaceuticals, cosmetics and food additives to high-volume materials such as biopolymers or chemical feedstocks, including platform chemicals
Bioflocculant	Biobased substance that causes aggregation of fine, dispersed organic particles and even microorganisms
Bioprocess	Specific process that uses microorganisms or enzymes to obtain desired products
Biorefinery	Integrative, multifunctional overarching concept that uses biomass as a diverse source of raw materials for the sustainable generation of a spectrum of intermediates and products while ensuring the minimisation of waste products (see Section 2.2.1)
Bioremediation	Cleaning contaminated soil or water using microorganisms or plants
Biosurfactant	Diverse group of surface active molecules and chemical compounds synthesised by microorganisms that reduce surface tension, stabilise emulsions, promote foaming, are which are non-toxic and biodegradable
Circular economy	An alternative to a traditional linear economy (make, use, dispose) in which we keep resources in use for as long as possible, extract the maximum value from them while in use, then recover and regenerate products and materials at the end of each service life www.wrap.org.uk/about-us/about/wrap-and-circular-economy
Commodity products	Also, bulk products Large-volume, low-price, homogeneous, and standardised chemicals produced in dedicated plants and used for a large variety of applications, petrochemicals, basic chemicals, heavy organic and inorganic chemicals (large-volume) monomers, commodity fibres, and plastics http://www.worldcat.org/wcpa/servlet/DCARead?standardNo=9780470050750&standardNoType=1&excerpt=true
Drop-ins	Biobased products chemically identical to their petrochemical counterparts
Economy of scale	Reduction in cost-per-unit-produced resulting directly from increased size of production facility
Feedstock	Raw material used as the basis for an industrial process

Fine chemical	Complex, single, pure chemical substances produced in limited quantities in multipurpose plants by multistep batch chemical or biotechnological processes, identified according to chemical formula http://www.worldcat.org/wcpa/servlet/DCARead?standardNo=9780470050750&standardNoType=1&excerpt=true
Industrial ecology	Systematic study of material and energy flows in products, industrial processes, and economies focusing on the interaction of industrial and the ecological systems of which they are a part
Macrophyte	Aquatic plant (growing in or near water) – emergent, submerged or floating
Meta-research	Research systematically combining and integrating data and analyses from multiple studies to develop more powerful conclusions and resolve or highlight conflicting areas Includes research studying research practices including methods, reporting, reproducibility, evaluation and incentives
Non-renewable resources	Natural resources of economic value that cannot be replaced by natural means on a level equal to consumption
Novel biobased products	New chemicals and materials from renewable raw materials with unique characteristics that are often impossible or very difficult to produce from petrochemical raw materials
Platform chemical	Used as feedstock in subsequent chemical or biochemical industrial processes to manufacture a range of consumer products
Renewable resources	Natural resources of economic value that are replaced through cultivation, natural growth or deposition at a rate commensurate with consumption
Resource recovery	Process of obtaining matter or energy from waste materials
Sankey diagram	A type of flow diagram in which the width of the arrows is proportional to the flow quantity
Soil conditioner	Organic or inorganic materials added to soil to improve its properties (cation exchange capacity, pH, water holding capacity, compaction)
Specialty chemicals	Formulations of chemicals containing one or more fine chemicals as active ingredients identified according to performance properties; for example: adhesives, agrochemicals, biocides, catalysts, dyestuffs and pigments, enzymes, electronic chemicals, flavours and fragrances, food and feed additives, pharmaceuticals, and specialty polymers http://www.worldcat.org/wcpa/servlet/DCARead?standardNo=9780470050750&standardNoType=1&excerpt=true
Valorization	Process of using chemical or biological methods to increase the value of a material by changing it – in particular here, producing products of value from a feedstock otherwise regarded as waste
Wastewater biorefinery	A biorefinery (see above) operating in the wastewater arena and designed to generate products of value-from-waste nutrients and simultaneously produce clean or "fit for purpose" water as the non-negotiable product (see Section 2.3)

1 INTRODUCTION

1.1 Challenges Driving New Approaches to Wastewater

It is well recognised that humankind is using the Earth's resources and creating a waste burden at a faster rate than nature can replenish. The seminal analysis of Wackernagel et al. (2002) demonstrated that the balance of resources used or degraded versus those available per capita passed the balance point around 1980. Since then, a steady degradation of our natural capital has been occurring. Some nations are exploiting this natural capital more than fivefold the rate of its replenishment. For many developed countries, this ratio is around threefold. For South Africa, it lies between 1.2- and 1.8-fold, yet many South Africans do not have an acceptable quality of life.

These findings may be superimposed on the increasing shift from the closed natural cycles to an open system of consumption and waste generation, demonstrated in Figure 1. To address the environmental burden on our planet, end-of-pipe treatments and waste minimisation have been considered. However, ongoing urbanisation and industrialisation drive the geographic separation of resource requirement and waste generation, including wastewaters, which require a new approach.

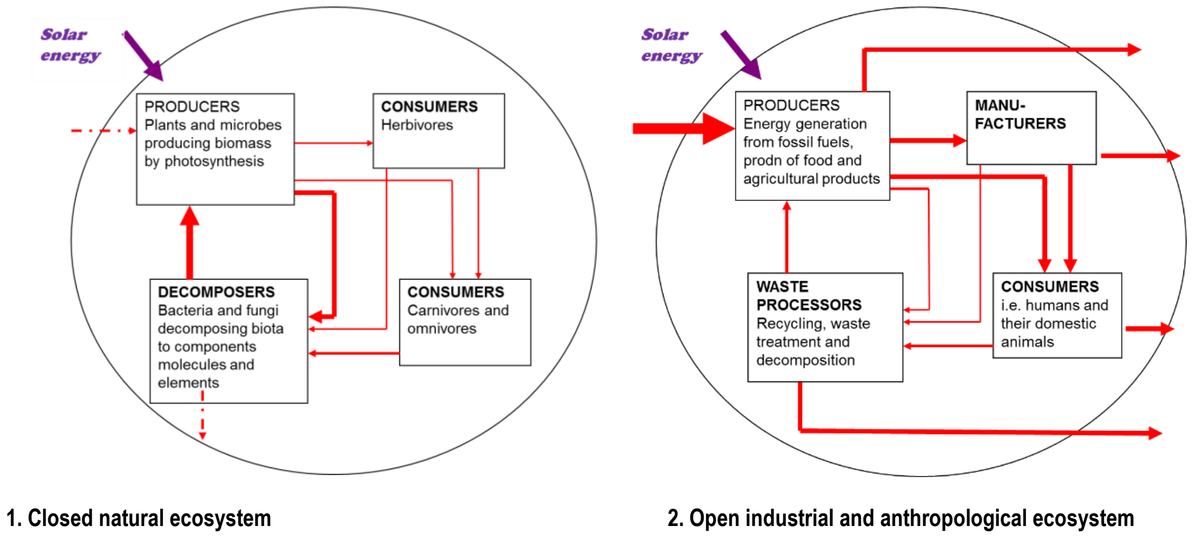


Figure 1: Demonstrating the need for closure in our anthropological and industrial ecosystems

With the growing demand for water driven by the increasing population and its quality of life, water demand is expected to exceed water supply through conventional approaches. Further, impacts of climate change may aggravate this on a regional basis. Hence, alternative sources of water are sought to address water scarcity. One of these alternative sources is increasing water recycling.

In addition, with the ongoing depletion of natural resources and the growing demands of our expanding and developing society, alternative and renewable sources of materials, chemicals, energy and fuels to the traditional fossil fuel based resources are sought. Because of this push away from fossil fuel based materials, there has been a surge of interest in using biological systems to produce biofuels, energy and chemicals. This transition has been nurtured by several countries implementing "bioeconomy strategy" or "biobased economy strategy" policies specifically geared towards growing this sector of the economy, giving rise to many widely used bioprocesses. This is premised on a reduced use of fossil resources and increasing dependence on renewable resources.

Traditional examples of bioprocesses geared towards replicating and replacing existing petrochemical-based systems include bioethanol production particularly in Brazil, biodiesel production in the European Union, and polylactic acid or starch-based polymers replacing plastics. Typically, these processes use agricultural ‘virgin’ products or by-products as feedstocks. Examples of the use of fairly pure, and relatively expensive, feedstocks include glucose or sucrose syrups for ethanol production, vegetable oils for biodiesel production, or glucose for a variety of bioprocesses producing commodity products. The requirement for these clean feedstocks puts economic pressure on these processes: economically as the feedstocks often account for most of the operating cost of the process (Grotkjær, 2016), environmentally with agricultural feedstocks contributing significantly to the environmental burden (Harding, 2009; Harding, et al., 2007), and socio-economically due to the competition between the production of food and the production of agricultural feedstocks for biobased chemicals or biofuel.

In contrast to these ‘traditional’ bioprocesses, biological systems can use by-product streams and streams that form the effluents or waste products of other processes. These are by nature streams of variable composition, variable flow rates, multiple and changing components. For the most part, bioprocesses for synthesising products of value and those processing effluents and waste streams have been traditionally been considered separately using quite different processing approaches. With the former, the product is all-important and the feedstocks are considered a cost. With the latter, the quality of the water is all-important and the feedstocks present are considered as contaminants to be removed from the liquid phase to gaseous or sludge components that are benign, but without value. The notable exception is biogas-producing anaerobic digestion where waste organic materials are converted into methane for use as an energy source and, potentially, volatile fatty acids (VFAs) as a feedstock for remediation (Harrison, et al., 2014) and commodity processes (Kleerebezem, et al., 2015). Currently, the separation between these two types of bioprocesses is significant: on the traditional bioprocessing side, pure feedstocks are used to produce specific products; on the waste water treatment side, varied streams are processed to produce clean water with little focus on the products of converting the carbon, nitrogen and phosphorous resources within the feedstock or recovery of value within the waste stream.

There is a need to both maintain our water resources (preventing their degradation through pollution) and maximise resource productivity, namely, maximising the use of each resource we exploit while minimising environmental burden. The integration of these two goals with associated improved efficiencies and productivity is the motivator to develop wastewater biorefineries (WWBRs) in which water treatment and optimising resource productivity are integrated through the sustainable processing of the wastewater into a spectrum of marketable products (chemicals and materials), energy and clean water (adapted from IEA Bioenergy Task 42 (n.d.)). The opportunity for this approach is clear when one considers that typical municipal wastewater contains ninefold the chemical energy required for its treatment (Shizas & Bagley, 2004), yet we commonly input a significant fraction of the municipal energy to treat the water with no combined products. This was confirmed by the analysis of South African wastewaters in 2007 in WRC K5/1732 (Burton, et al., 2009) where it was shown that energy recovery from wastewater could provide a significant contribution to South Africa’s energy provision. A variety of technologies, including heat recovery, biomass production with subsequent combustion and gasification, biogas production, bioethanol production and microbial fuel cells, could contribute towards energy products.

This project aims to outline and examine a relatively new thinking at the intersection between traditional bioprocessing and wastewater treatment to utilise waste streams as a valuable substrate for commodity bioproducts, rather than a liability simply to be cleaned sufficiently. This concept can be termed the “wastewater biorefinery” where focus is on liquid effluents or more generically the “waste biorefinery”. While the concept of biorefinery within literature has generally focused on biorefineries that convert cellulosic biomass as a feedstock, the subject of this study can be defined as distinct by focusing on a substantial and underutilised resource, namely, wastewaters. The consideration of wastewaters for biorefining has been a recent development in literature, being tabled for the first time around 2007/2008 (Mooibroek, et al., 2007; Werker, 2008). However, significant research and some preliminary implementation has taken place, for the most part in a European setting.

Implementing WWBRs moves industrial production towards closing resource cycles by recapturing those components of wastewaters that have value and reinserting them into economic circulation while at the same time remediating wastes and recovering clean water as a product, thus creating a circular economy. This approach is consistent with both the concepts of industrial ecology and cleaner production.

In this document, we focus on the potential of WWBRs in South Africa and the development of key aspects of these. The potential to view wastewater streams as both a potential water resource and a resource of nutrients to fuel bioprocesses for commodity product formation is considered. Local and global research centred on, or applicable to WWBRs is reviewed. Wastewater streams with potential to be used as feedstock are highlighted along with the technical requirements for such, including which biological systems and reactor configurations may be appropriate. Several examples of potential products from WWBRs are presented. A generic WWBR flowsheet and an associated material balance model have been compiled. This is used to explore several hypothetical WWBR flowsheets for several South African wastewaters. The compilation of these findings allows the potential value of the WWBR in South Africa to be considered.

1.2 Project Scope and Limitations

Providing water of suitable quality and treating wastewater are high priorities, both globally and specifically locally in water scarce South Africa where currently eight of the nine provinces have been declared drought disaster zones (Reuters, 2016). In most countries, compliance requirements have become more stringent with increasing recognition of the impact of poor water quality on the quality of human life and the environment. There is an impending water scarcity in many parts of the world, including South Africa, with growing water demand and increasing wastewater generation resulting from an increase in human population, standard of living and industrialisation.

The first priority for water use and wastewater generation should always be to minimise both waste production and water use through cleaner production approaches and integration of closed systems. Where this cannot be achieved or is only partially achieved, the concept of WWBRs can further minimise waste generation and water use within a larger “system boundary”.

Typically, wastewater treatment is considered an expense, with its associated treatment and energy costs. It is focused on remediating water to environmental quality rather than on the direct application thereof for particular use. Approaching wastewater from a different perspective, we consider wastewater as a potential feedstock to produce both compliant water or water “fit for purpose” for its next use, and to produce other products using the organic carbon, nitrogen and phosphorus nutrient components of the wastewater streams. Such perspectives are aligned with water-sensitive urban designs and the principle of industrial ecology.

The WWBR is designed and optimised with the aim of ensuring both the effective treatment of water to the necessary standard (yielding “clean” and “fit for purpose” water as a product), and the conversion of the components removed from the wastewater to products of economic and/or social value.

Due to the dilute nature of wastewaters, many typical bioprocess configurations and bioreactor designs are not appropriate. Because of the non-sterile nature of the wastewater environment and impracticality of sterilisation, the use of mixed microbial consortia is required. Hence, it is imperative that the microbial community of interest is selected by choosing the culture conditions and environment that provide selective advantage. This means that WWBRs are not suitable for all bioproducts.

To investigate the potential of wastewaters as a resource for biobased products in South Africa and to identify potential products suitable for production from wastewater with simultaneous upgrading of the water resource, the wastewater inventory needs to be better understood. This requires good quantification of wastewater generation and of the components in the various wastewaters. In a study by Cloete et al. (2010), information on South African wastewaters was obtained from numerous companies in the industrial, food and beverage, mining and electricity generation sectors; however, most companies contacted did not perform analyses on the full spectrum of substances in their effluent, therefore limiting the completeness of the data gathered. Currently, updated information is being collected through the Water Research Commission’s (WRC) National Industrial Water and Wastewater

Survey (NatSurv) studies; however, the outcome of these is not yet available. At time of writing, there is still no system for regulating exactly what information on effluent production must be gathered by metropolitan councils, especially regarding chemical composition. As a result, the data obtainable from metropolitan councils is inconsistent and clear comparisons are not possible (Cloete, et al., 2010; WRC, 2015a).

To meet the requirements and challenges highlighted for this study, the following components have been considered within the extended scope of the study:

1. Review national and global research relevant to WWBRs.
2. Review potential example feedstocks for WWBRs with a particular focus on South Africa.
3. Propose some example products of a potential WWBR.
4. Develop criteria for successful biorefineries with particular focus on criteria for appropriate bioreactor systems.
5. Assess bioreactor systems currently used within wastewater treatment plants, or with potential to be used, and their potential for use in the WWBR.
6. Develop a flowsheet framework for WWBRs to facilitate assessment of their potential.
7. Build illustrative flowsheets using South African feedstocks to provide scenarios to investigate WWBRs and their key features.
8. Describe the WWBR concept with its potential and limitations.

1.3 Project Aims

In this study, we have set out to address the following aims:

- To review current research nationally and globally, focused on the valorization of waste through the "waste-to-resource" and biorefinery concepts.
- Building on our earlier studies reported in Verster et al. (2013), to identify a set of appropriate reactor designs for use in the WWBR to convert dilute organic streams in a non-sterile environment to a product of value, to refine these designs and to specify the factors guiding choice between these reactors.
- To explore the potential of a unit operation to convert soluble organic carbon in a partially treated wastewater stream to a polymer product of value (such as polyglutamic acid (PGA) through building on the outcomes reported by Verster et al. (2013)), through appropriate reactor design and microbial ecology – proof of concept at laboratory scale.
- To review the data available on the potential component processes to be included in the WWBR to meet its complementary needs of removing organics, nitrogen, phosphorous, processing of sludge and water polishing, using the open literature and, particularly the WRC database, to inform integration of these operations into the flowsheet and to provide data for material and energy inventories.
- To identify a potential set of component processes for the WWBR, allowing the selection of two to three process flowsheets to be developed.
- To define the required components incorporated into a WWBR conceptual plan relevant to South Africa.

Through discussions with the Reference Group during the project, the experimental reactor studies were de-emphasised. Further, we set about additional research beyond that originally scoped in the project to provide an initial description of examples of important wastewater streams in South Africa. It must be noted here that the level of available information is currently constrained, which limits the detail of this study. This is expected to be partly remedied through the new NatSurv documents in preparation.

Project deliverables specified at the outset of the project are given in Table 1. Any deviations from project scope agreed in discussions with the Reference Group throughout the project are given as well.

Table 1: Project Deliverables

#	Deliverable	Deliverables specified in proposal	Alterations
1 (D)	Overviewing and developing the WWBR concept for application in South Africa	• Review of global and national research and development (R&D) trends related to biorefineries and "waste-to-resource" in the wastewater and sanitation space. • Review of wastewater valorization research in South Africa, mining R&D reports of WRC in particular. • Develop examples of the biowaste biorefinery, drawing on both new and existing South African examples of suitable unit operations with economic evaluations. • Definition of a WWBR conceptual plan(s) relevant to RSA.	
	Review of South African wastewaters to provide example feedstocks		Overview of a selection of example wastewaters with respect to composition and abundance was undertaken following discussions with the Reference Group
2 (A)	Reactor selection as a key system component for value from waste	• The review of reactors with application in WWBRs will be expanded based on criteria specified. • Following selection of two reactor designs, design, construction and commissioning will take place at the 5-20 ℓ scale.	
3 (B)	Products from dilute organic streams	• Overview of example of polymer products for production from wastewater. • Report on performance of polymer process, describing conversion, product quality and recovery, microbial ecology. • Provide a literature review on microbial polymer production.	Focus on the experimental study and proof of concept was de-emphasised to enable the "big picture" study to progress as focal point
4 (C)	Component processes for the integrated biorefinery	• Initial biorefinery process flowsheets will be proposed. • Material and energy inventories on the hypothetical WWBR flowsheet for integration into biorefinery. • Provide integrated process flowsheet of two to three process configurations of the WWBR.	

2 WASTEWATER BIOREFINERY REVIEW: GLOBAL AND NATIONAL PERSPECTIVES

The WWBR concept is gathering interest and is increasingly recognised for its potential contribution to the bioeconomy or biobased economy and its impact on the move towards cleaner production, an industrial ecology and circular economy. In this section, the bioeconomy strategies of some countries are introduced, the biorefinery concept is explained and the WWBR is introduced. Thereafter, examples of global projects utilising wastewater are summarised. These reviews lead to questions that need to be addressed to determine the possible application of WWBRs, their potential and their design.

2.1 National Bioeconomy Strategies

2.1.1 Establishing global bioeconomy strategies

Many countries including Ireland, Sweden, Norway, the Netherlands, Canada, United States of America (USA), Germany and the European Union have developed bioeconomy strategies (Bioeconomy in Action, n.d.) anticipating increased focus on biotechnology-based value generation. The first of these was published by the Netherlands in 2004 with most of the remainder published between 2011 and 2014. These strategies, with the focus of each summarised, are given in Table 2 (See also Section 2.1.2).

Table 2: Countries that have published bioeconomy strategies with the main focus of each (www.bioeconomy.dk)

Country	Bioeconomy strategy	Focus of strategy
Canada [4]	In July 2011, a “Bioeconomy Committee” was formed in British Columbia, Canada.	The Bioeconomy Committee formulated a set of recommendations for government to hasten productive economic development of British Columbia’s bioeconomy sector. The main pillars of the recommendations are: • Establish a clear, long-term bioeconomy vision. • Improve access to fibre and feedstock. • Establish a technology development strategy. • Develop markets for British Columbian bioproducts and aggressively market British Columbia’s advantages. • Integrate the bioeconomy’s infrastructure needs into provincial initiatives.
Europe [8]	On 23 February 2012, the European Commission released its strategy “Innovating for Sustainable Growth – A Bioeconomy for Europe”.	
Finland [7]	The Finnish Bioeconomy Strategy was published in August 2014.	The strategic goals of the Finnish Bioeconomy Strategy are: • A competitive operating environment for the bioeconomy. • New business from the bioeconomy. • A strong bioeconomy competence base. • Accessibility and sustainability of biomasses.
Germany [6]	The German Bioeconomy Council released its first recommendations in 2009 and second recommendations in 2011. It also has published a number of reports on bioeconomy potential and growth.	The research strategy defines five priority fields of action: • Global food security. • Sustainable agricultural production. • Healthy and safe foods. • The industrial application of renewable resources. • The development of biomass-based energy carriers.
Ireland [1]	Ireland published its Foresight Report in 2008 “Towards 2030 – Teagasc’s Role in Transforming Ireland’s Agri-food Sector and the Wider Bioeconomy”.	The four pillars are: • Food production and processing. • Value-added food processing. • Agri-environmental products and services. • Energy and bioprocessing.

Country	Bioeconomy strategy	Focus of strategy
Netherlands [5]	The Netherlands "Bio-based Economy" strategy was launched in 2004, funded through the profits of North Sea oil.	The working paper of the Netherlands focuses on: • The integrated approach. • The whole value chain of biomass. • Opportunities for agriculture. • A level playing field.
Norway [3]	Norway has published a preliminary research programme from 2012-2022 on "Sustainable Innovation in Food and Bio-based Industries", BIONÆR.	The following cross-cutting perspectives apply to all research activities under the BIONÆR programme: • Sustainable production and consumption, emissions reductions and adaption to climate change. • Improved resource efficiency in new and existing biomass production and full utilisation of all biological resources in closed-loop systems. • Focus on reducing food loss and discard and on using residual raw materials as a resource. • Further refinement of existing and development of new types of value-creating cross-utilisation between resource streams. • Further refinement of existing and development of new processes, products and services. • Enhanced value creation and competitiveness in the biobased industries, with a focus on market orientation and innovation in all segments of the various value chains.
Sweden [2]	The "Swedish Research and Innovation Strategy for a Bio-based Economy" was published in March 2012 by the Research Council for Environment, Agricultural Sciences and Spatial Planning.	The following R&D needs were defined: • The replacement of fossil-based raw materials with biobased raw materials. • Smarter products and smarter use of raw materials. • Change in consumption habits and attitudes. • Prioritisation and choice of measures.
USA [9]	In USA in April 2012, the Obama Administration released the bioeconomy strategy "US National Bioeconomy Blueprint".	The USA strategy has many similarities with the European strategy, and has five major objectives: • Support R&D investments that will provide the foundation for the future US bioeconomy. • Facilitate the transition of bio-inventions from research laboratory to market, including an increased focus on translational and regulatory sciences. • Develop and reform regulations to reduce barriers, increase the speed and predictability of regulatory processes, and reduce costs while protecting human and environmental health. • Update training programmes and align academic institution incentives with student training for national workforce needs. • Identify and support opportunities for the development of public private partnerships and precompetitive collaborations – where competitors pool resources, knowledge, and expertise to learn from successes and failures.

[1] http://www.teagasc.ie/Foresight/. Date accessed: 15 May 2014.
[2] http://www.formas.se/PageFiles/5074/Strategy_Biobased_Ekonomy_hela.pdf. Date accessed: 15 May 2014.
[3] www.http://bioeconomy.dk/Norway_Bionaer_programme.pdf. Date accessed: 15 May 2014.
[4] http://bioeconomy.dk/BritishColumbia_Bioeconomy_Report.pdf. Date accessed: 15 May 2014.
[5] http://www.bmbf.de/pub/Natinal_Research_Strategy_BioEconomy_2030.pdf. Date accessed: 15 May 2014.
[6] http://www.bmbf.de/pub/Natinal_Research_Strategy_BioEconomy_2030.pdf. Date accessed: 15 May 2014.
[7] http://biotalous.fi/wp-content/uploads/2014/08/The_Finnish_Bioeconomy_Strategy_110620141.pdf. Date accessed: 8 August 2016.
[8] http://ec.europa.eu/research/bioeconomy/pdf/201202_innovating_sustainable_growth_en.pdf. Date accessed: 15 May 2014.
[9] http://www.whitehouse.gov/sites/default/files/microsites/ostp/national_bioeconomy_blueprint_april_2012.pdf. Date accessed: 15 May 2014.

2.1.2 *The South African bioeconomy strategy*

South Africa has built on its National Biotechnology Strategy of 2001 (DST, 2001), launching a bioeconomy strategy in 2013. While this strategy was drafted by the Department of Science and Technology (DST), it has the buy-in of multiple ministries including the Department of Higher Education and Training, Department of Water Affairs Fishery and Forestry, Department of Trade and Industry and others. In this strategy, cooperation between industry, science councils, government departments and academia is highlighted to ensure that bioprocesses, biotechnology and bioinnovations are market relevant for easy application in South Africa. The three foci of the strategy are health, agriculture, and industrial bioprocesses and the environment (DST, 2013). All three areas have implications in water use and treatment, as bioprocesses and biotechnology are fundamentally water-based. Water, waste and the environment are specifically addressed in the implementation plan under development for the industrial bioprocess and environment component of the South African strategy.

2.2 The Biorefinery Concept

2.2.1 *Defining the concept*

A biorefinery is characterised as an integrative, multifunctional, overarching concept that uses biomass as a diverse source of raw materials for the sustainable generation of a spectrum of intermediates and products (chemicals, materials, bioenergy and fuels) while including the fullest possible use of raw material components (i.e. maximising resource productivity) and minimising waste products. Co-products can also be food or feed. These objectives necessitate the integration of a range of different methods and technologies. The biorefinery process chain includes the pretreatment and preparation of biomass, the separation of biomass components (primary refining), subsequent conversion and processing steps (secondary conversion), and subsequent separations (De la Fuente, 2014).

Most commonly, biorefineries refer to the use and beneficiation of biomass and consider lignocellulose as a main starting material (Fernando, et al., 2006; Kamm, et al., 2006). Many initiatives for biomass valorization focus on fermentation of the whole raw material to low-value energy carriers such as biogas or ethanol, also known as low-value high-volume products. It is, however, potentially more economically sustainable to produce high-value low-volume products from this biomass and its associated side streams and use residual fractions for conversion to biogas or other energy carriers (Wolkers, et al., 2011).

2.2.2 *Classification of biorefineries*

Biorefineries can be classified in several ways based on their system components (IEA Bioenergy, n.d.), namely, platforms, products, feedstocks, and conversion processes as explained below:

Platforms: These refer to intermediates that connect different biorefinery systems and their processes. The number of platforms is an indication of the system complexity. Five platform biorefineries are currently recognised (Nieddu & Vivien, 2013):

- Sugar platform.
- Thermochemical/syngas platform (gasification of biomass feedstocks).
- Biogas platform (produces cooking gas – CO_2 and methane).
- Carbon-rich chains platform (produces biodiesel).
- Plant products platform (the plant is operated as a biorefinery).

Products: Two biorefinery product groups are recognised, namely:

- Energy products such as bioethanol, biodiesel and synthetic biofuels.
- Material products such as chemicals, materials, food and feed.

Feedstocks: These can be grouped as:

- Energy crops from agriculture (e.g. starch crops, short rotation forestry).
- Biomass residues from agriculture, forestry, trade and industry (e.g. straw, bark, used cooking oils, waste streams from biomass processing).
- Wastewater, wastewater-associated sludges and solid waste as a feedstock are not presented in any of the work from which this analysis was drawn, but are recognised by the authors as a key opportunity.

Conversion processes: Currently there are four major groups of conversion processes involved in biorefinery systems, namely:

- Biochemical (e.g. fermentation, enzymatic conversion).
- Thermochemical (e.g. gasification, pyrolysis).
- Chemical (e.g. acid hydrolysis, synthesis, esterification).
- Mechanical (e.g. fractionation, pressing, size reduction).

2.2.3 The three biorefinery generations

First generation biorefinery processes were dedicated to producing biodiesel and ethanol, based on "a single raw material, a single major product". These systems are limited since by-products are produced; therefore, the management of these co-products must be considered. For example, biodiesel production generates a major by-product, glycerol, which must be used for the approach to succeed.

Second-generation biorefinery processes are also based on the processing of a single raw material, but focus on creating a range of products and using all the biorefinery co-products, thereby extracting a whole range of products for energy, chemicals and other materials. The feedstocks may also be termed first, second or third generation: arable crops, non-food biomass (such as agricultural residue, woody biomass and lignocellulose), and algae or waste materials. Existing second-generation biorefineries use less than 20% of the biomass feedstock for ethanol production. Major side streams are produced, such as pentose and lignin waste streams that are used for biogas and energy production. Converting the carbon from these waste streams into value-added products is expected to increase the otherwise low profitability and improve the environmental benefits of the biorefineries (Biorefine2g.eu, 2013).

Third-generation biorefineries have been proposed and are an emerging concept set to reach maturity as an integrated process around 2020. Sharing the same multi-product approach as the previous generation, the third-generation integrated biorefinery can incorporate a combination of any of the five platforms. Third-generation biorefineries diverge in two ways from second-generation biorefineries. Firstly, third-generation biorefineries should be capable of using different types of raw materials and transformation technologies. Secondly, they should be capable, depending on price developments, of modifying the technical itineraries to reverse the hierarchies between key products and sub-products. This approach of flexibility to select the most profitable combination of raw materials and processes relies on a vision of the ideal production tool that is fully adaptable to market fluctuations.

WWBRs complement conventional biorefineries by providing additional resources to enable this value addition. The WWBR would, of necessity, be a third-generation biorefinery because of the complex and variable nature of the raw material. Following the De la Fuente definition (De la Fuente, 2014), it would make the fullest possible use of all raw material components, producing clean or "fit for purpose" water as one of the products.

2.3 The Wastewater Biorefinery

A WWBR, as an example of a third-generation biorefinery, needs to both generate products of sufficient value to be economically viable, and produce products of variable value concomitantly with production of clean water as a product, typically through multiple unit operations. This concept views wastewater treatment as an integrated system rather than a unit process. It potentially provides a link between the users of water and those responsible for its management where resources are recovered in closed-loop cycles, thus contributing towards the concept of a circular economy (IEA Bioenergy, n.d.).

In contrast to these 'traditional' bioprocesses, biological systems can also use complex or 'dirty' streams, i.e. non-sterile streams of variable composition and flow rate with multiple and changing components. Conventional biological systems have been developed to remediate wastewater streams to produce sufficiently clean water with little regard for producing any other products. A notable exception to this is biogas-producing anaerobic digestion that converts waste organic materials into methane to use as an energy source while decreasing the organic loading as part of water treatment.

A WWBR operates in the wastewater arena; however, it is designed to generate products of sufficient value from the waste nutrients for economic viability while simultaneously producing clean or "fit for purpose" water as non-negotiable product. This concept positions wastewater treatment as part of an integrated system rather than an "end of process" unit. The WWBR comprises a set of processes that can be assimilated into the operations of either the wastewater producers or the wastewater treatment.

The WWBR, or even "global and national R&D trends related to biorefineries and 'waste-to-resource' in the wastewater and sanitation space" (IEA, 2014), exists only as a nascent concept at this stage, proposed by a few research groupings. Implementation is yet to be realised. Most approaches recorded towards the WWBR are currently still in the first- and second-generation biorefinery process stages, where the products from wastewater and sanitation are directed towards a combination of biogas, compost or biofertiliser.

This project seeks to contribute to defining and developing the WWBR concept. Figure 2 illustrates a potential WWBR process flowsheet using municipal wastewater as its raw material. This conceptual development was initiated as part of the study conducted in WRC K5/2000 and reported by Verster et al. (2014). The unit processes typically found in a functional wastewater treatment works (WWTW) using biological nutrient removal are adapted to facilitate product recovery. Typically, there are multiple unit processes in the WWTW to enhance overall process performance and resilience. It is proposed that some of these unit processes are adapted for commercial production depending on the characteristics of the incoming waste stream(s), surrounding market needs and similar factors.

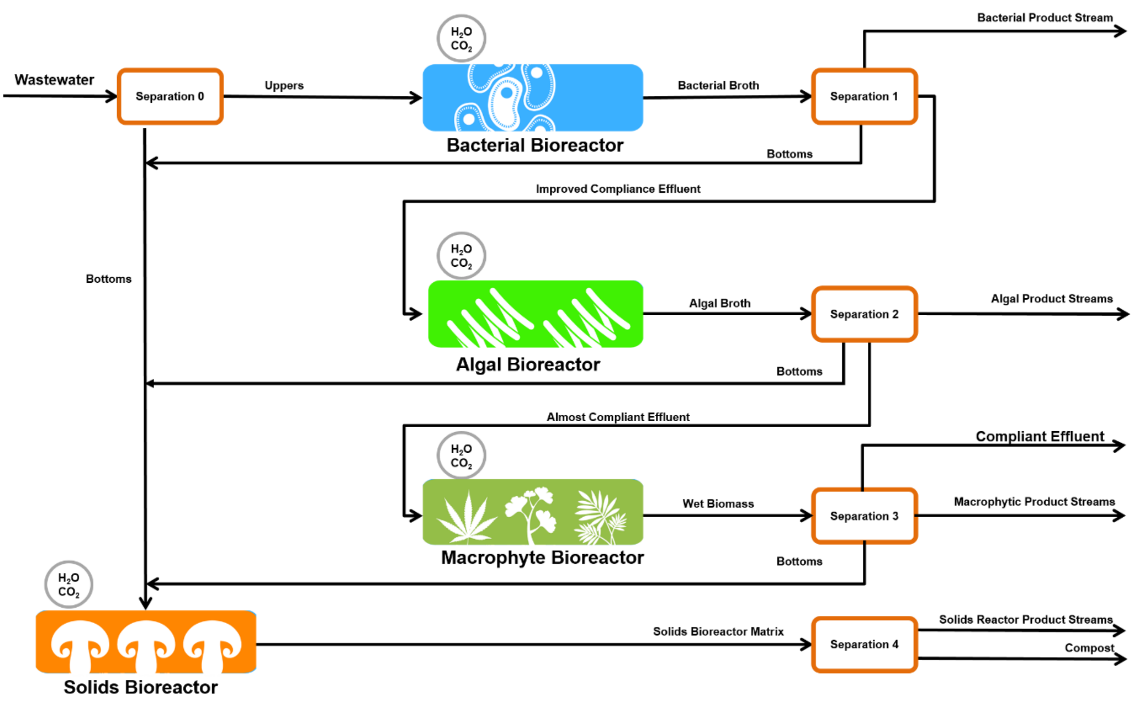


Figure 2: A simplified flowsheet of a potential WWBR

2.4 Global Research Around Wastewater Biorefineries

2.4.1 Conferences and initiatives relevant to WWBRs

International Conference on Renewable Resources and Biorefineries (RRB)

The annual RRB is used here as an indication of the progression of research in this field. This conference series started in September 2005 to allow delegates from university, industry, governmental and non-governmental organisations, as well as venture capital providers to present their views on industrial biotechnology, sustainable (green) chemistry and agricultural policy related to the use of renewable raw materials for non-food applications and energy supply. The conference further aims to provide an overview of the scientific, technical, economic, environmental and social issues around RRBs to give an impetus to the biobased economy and to present new developments in this area. The conference provides a forum for leading political, corporate, academic and financial people to discuss recent developments and set up collaborations (www.rrbconference.com).

The RRB conference focus has been on:

- Starch biorefineries.
- The integration between agriculture and chemistry for biorefineries.
- The production of biopolymers as well as cellulosic biorefineries.

At the fourth RRB in 2008, the production of products of value from wastewaters was first mentioned:

RRB-4 2008; a single presentation on value from wastewaters:

- Alan Werker from AnoxKaldnes Biopolymer (Sweden) presented "Production of biopolymers as a by-product of industrial wastewater treatment".

RRB-7 2011; two presentations of value regarding wastewaters:

- Bernelle Verster from the University of Cape Town (South Africa) "Producing poly-glutamic acid from wastewater using Bacillus: Considerations when moving from bioprocess to environmental engineering".
- Jean-Philippe Steyer from Institute for Agricultural Research INRA (France) "Anaerobic digestion for waste/wastewater treatment and bioenergy production: Shouldn't we get inspired by Mother Nature?"

RRB-8 2012: five presentations relating to the biorefinery concept, but no specific mention of WWBRs:

- PhD short communication: Sofia Tsakona from the Agricultural University of Athens (Greece) "Production of generic fermentation feedstock from flour based industrial waste streams".
- John A. Posada from Utrecht University (Netherlands) "Integrating the concept of biorefinery on a biodiesel production plant: fuel, chemical and energy production".
- Geneviève Doreau from Maguin (France) "The concept of a biorefinery: Looking to the future".
- Valérie Vandermeulen from Ghent University (Belgium) "Industry's expectations regarding the transition towards a biobased economy".
- Han Vervaeren from Howest (Belgium) "Wastewater treatment with microalgal bacterial (MaB) flocs: From lab to pilot scale".

RRB-9 2013; five presentations on using wastewater and third-generation biorefineries:

- Kees Roest from Watercycle Research Institute (Netherlands) "Water resources".
- Carl Dewaele from NuReSys (Belgium) "P recovery from municipal WWT plants".
- Michel Eppink from the University of Wageningen (Netherlands), "Biorefinery of microalgae: Production of high-value products, bulk chemicals and biofuels".
- Erika Cristina Francisco from the University of Campinas (Brazil), "Production of high cell density of Cyanobacterium phormidium sp. using cassava wastewater".
- Antonis Kokossis from the National Technical University of Athens (Greece) "Integrated designs of microalgae biorefineries using a fixed selection of halophytic algae".

RRB-10 2014; relevant presentations increased to seven:

- Germán Buitrón from the Universidad Nacional Autónoma de México (Mexico), "Biohydrogen production using tequila vinasse wastewater".
- Bernelle Verster from the University of Cape Town (UCT) (South Africa), "Wastewater biorefineries: Recovering value while producing cleaner water".
- Boudewijn Meesschaert from Leuven University (Belgium), "Calcium phosphate precipitation in anaerobic effluent of potato processing industry is promoted by preceding nitrification".
- Cedric Tarayre from Gembloux University (Belgium), "Biorefine: Recovery of nutrients and metallic trace elements from different wastes by chemical and biochemical processes".
- Wilhelmus J. Mulder from Wageningen University (Netherlands), "Biorefinery and the potential of proteins from side streams".
- Alexandre Besson from LISBP (France), "Microalgae harvesting for biorefineries valorisations: Scale up of an autoflocculation-flotation process".
- Paulien Harmsen from Wageningen University (Netherlands), "Biorefinery of seaweed (or macro algae): Which way to go?"

RRB-11 2015 saw an even greater emphasis on waste biorefineries, with increased focus on the peripheral requirements such as integration and downstream processing (DSP), with 12 relevant oral presentations:

- Paulo Coutinho, Braskem (Brazil), "Brazilian Biorefinery: An evolving model" presented in the opening plenary session".
- Paulo Coutinho, Braskem (Brazil), and Stefanie Kluge, AVT-RWTH Aachen University (Germany), "Enzymatic production of acetylated cello-oligomers from water-soluble cellulose acetate".
- Oscar Avello, Centro de Estudios en Alimentos Procesados (Chile), "Microalgae cultivation using liquid waste streams from fruit and vegetable processing plants as growth medium for biomass and biofuel production".
- Vania Zuin, Federal University of Sao Carlos (Brazil), "Downstream processing and biorefinery separation challenges: new perspectives on chromatographic methods".
- Anthony Lloyd, Novasep Process (UK), "Separation and purification, the missing link between biomass deconstruction and commercial product".
- Diogo Queiros, University of Aveiro (Portugal), "Short-chain fatty acids production through acidogenic fermentation of hardwood sulphite spent liquor".
- Davide Mainero, ACEA (Italy), "The ACEA Pinerolese experience in the management of municipal biowastes and research on their valorization as source of biofuel and added value products".
- Rommie van der Weide, WageningenUR (Netherlands), "Recycling nutrients and valorise side streams in local biorefineries".
- Mette Lubeck, Aalborg University Copenhagen (Germany), "Mixed cultures of fungi for conversion of lignocellulose into bioproducts".
- Md Ariful Haque, City University of Hong Kong, "Valorization of food waste for bio-colorant (Monascus dye) production".
- Federica Zaccheria, ISTM CNR (Italy), "Beyond dedicated crops: The waste biorefinery".
- Merten Moralsed, ETH Zurich, Switzerland, "Integrated biorefinery concepts for polypropylene production from palm oil and wood residues".

RRB 2015 also featured 11 relevant posters:

- Y. Hu, et al. (Hong Kong and China), "Conversion of food waste into polylactic acid fibre".
- Alexandra Lanot, J. Sloan, Y. Li, S. McQueen-Mason (UK), "MultiHemp: A knowledge-driven effort to develop a hemp-based biorefinery".
- Margarita María Andrade-Mahecha et al. (Columbia), "Use of sugar cane bagasse for the improvement of the mechanical properties of paper".
- Gianluca Ottolina, S. Gandolfi, L. Pistone, P. Xu, S. Riva (Italy & China), "Hemp hurds biorefinery: Production of L-(+)-lactic acid".
- Xu Zhang, T. Tan (China), "From waste bioresources to bioenergy and chemicals".
- Sofia Raikova, C. Chuck, V. Ting (UK), "Valorisation of microalgae used in remediation of mine waste".

- S. Grivot, K. Tomono, Thierry Talou (France & UK), "VFWV wheel: An interactive model illustrating EUB is network valorisations of vegetables & fruits wastes".
- Sophie Roelants, et al. (Belgium) "Microbial biosurfactants: Closing the gap in the innovation chain".
- Ferrer, (Spain), "Bioenergy and bioproducts from microalgae grown in wastewater".
- V. Liakou, (Greece), "2,3-butanediol production from fruit and vegetable waste streams".
- Nefeli-Maria Georgaka, M. (Greece), "Development of an advanced biorefinery concept based on valorization of winery wastes".

Reneseng

This is a renewable systems engineering initiative that was launched towards the end of 2013 with funding from a European Consortium to the value of €4.2 million. The aim of the project is to contribute to research and training of engineers with project experience in biorefineries and emphasis on advanced process design, synthesis, model-based screening and analysis and process integration. To this end, two workshops have been held in April 2014 and March 2015. The first workshop introduced biorenewables and biorefineries, with attention given to the logistics of the project itself. The focus of the second was the use of process systems engineering tools in the biorefinery space. A course entitled "Renewable Systems Engineering" was held at Delft University of Technology (TU Delft) in November 2014. The Reneseng Project has 11 full partners: seven academic and four private partners. The project is scheduled to conclude four years after initiation: towards end of 2017 (Reneseng, n.d.).

International Water Association (IWA) Resource Recovery Conference (IWARR)

In late 2015, the first IWA Resource Recovery Conference (IWARR2015) was held in Ghent, Belgium (IWARR2015, 2015). This promising development was the first conference dedicated to the interface between water treatment and resource recovery. Two presentations focused on data gathering, which remains one of the main challenges when moving towards resource recovery:

- M Papa from the University of Trento (Italy), "How far are we from closing the loop of resource recovery? A real picture of municipal wastewater treatment plants".
- JP van der Hoek from Waternet/TU Delft (Netherlands), "Wastewater as a resource: Strategies to recover resources from Amsterdam's wastewater".

The main resource recovery routes remain focused on a limited number of products, namely, struvite, biogas and PHA, illustrated in Mark van Loosdrecht's (TU Delft, Netherlands) presentation "Wastewater: What are the potentials for resource recovery?". Other potential product streams include cellulose and alginate. Veolia is an industry leader regarding polyhydroxyalkanoate (PHA) production, and was strongly represented:

- A Werker from Veolia (France), "Bridging upstream and downstream stakeholder needs for regional biopolymer value chains built on residuals management services".
- M Hjort from Veolia Water Technologies, AnoxKaldnes (Sweden), "PHA as municipal wastewater treatment by-products: A polymer production demonstration project: PHARIO".

While the conference aimed to contribute to the circular economy concept, the field still struggles to define what this means. Kees Biesheuvel from SmartDeltaCluster (Netherlands) illustrated a successful case study titled "Industrial symbiosis, a human challenge".

A compendium report on resource recovery from water was released at the same time, by the IWA Resource Recovery Cluster (http://www.iwa-network.org/cluster/resource-recovery-from-water-cluster [Accessed: 10 February 2016]). This document gives an overview of the state of the industry and aimed at "creating awareness of the issues involved, and are particularly meant to activate readers from different backgrounds towards the conceptual but also pragmatic approaches of 'cleantech' in the water business" (Holmgren, et al., 2015, p. 2). The report incorporates data gathered from a survey targeting water professionals in academia and industry. Unfortunately, there was little participation from stakeholders in Africa (Holmgren, et al., 2015).

2.4.2 European facilities creating value from wastewater

In European countries, especially the Netherlands and Denmark, several pilot- or industrial-scale facilities have been developed in recent years and are operating and creating value from wastewater. These examples of global progress are reviewed in Table 3. Researchers in the Netherlands and Denmark are international leaders in the field.

Table 3: Companies in Europe producing value from wastewater

Country	Company	Industries	Wastewater	Product	Scale (demo, pilot or industrial)	Volume if applicable
Netherlands [1]	Plant built by Paques BV		Chocolate wastewater from Mars factory	Bioplastic PHAs	Pilot plant (Nov 2012 to end 2013)	–
Denmark [2]	Kalundborg (example of integrated biorefinery)	Symbiosis between five companies: Asnæs power station, plasterboard makers Gyproc, pharmaceutical and biotechnology firms Novozymes and Novo Nordisk, soil cleansing company Soilrem and Statoil refinery	• Wastewater from Novo Nordisk and Novozymes • Sludge from municipality's water treatment plant	• Biofuel (see next entry) • Fertilisers distributed to local farmers • Final product used as an additional soil nutrient	Industrial	150 000 t of fertilisers was produced in 2010
Denmark [3]	Novozymes and Novo Nordisk	Novozymes and Novo Nordisk in Kalundborg facility	Wastewater from the factories in Kalundborg	Biofuel (biogas)	Industrial	Biogas reactor produces up to 47 000 MWh of electricity p.a.
Denmark [4]	Krüger A/S, Billund Vand A/S, Billund Municipality, Danish Ministry of Environment and Vandsektorens Teknologiudviklingsfond Fonden (Water Sector Technology Development Foundation)	Billund BioRefinery	Domestic, industrial and agricultural wastewater	Biogas, organic fertiliser, bioplastic	Demo plant	
Netherlands [5]	Nijhuis Water Technology	Outsourcing wastewater technology available to companies	Wastewater from industries	Biogas, fertiliser	Industrial	

[1] DELTA, 2013. Living on water from Mars [Online], Available at: http://delta.tudelft.nl/artikel/living-on-water-from-mars/26740, [Accessed: 8 October 2014].
[2] Global Lamp Index, 2011. The Kalundborg Symbiosis A model of progressive resource exchanges [Online], Available at: http://www.lampindex.com/2011/10/the-kalundborg-symbiosis/, [Accessed: 8 October 2014].
[3] Novozymes, 2013. Novozymes utilises wastewater to produce biogas [Online], Available at: http://novozymes.com/en/news/news-archive/Pages/novozymes-utilizes-wastewater-to-produce-biogas.aspx, [Accessed: 8 October 2014].
[4] Billund BioRefinery, 2014. Billund BioRefinery. [Online], Available at: http://www.billundbiorefinery.dk/en/, [Accessed: 2014 October 2014].
[5] Nijhuis Water Technology, 2014. Nijhuis Water Technology. [Online], Available at: http://www.nijhuis-water.com/default.aspx?taal=true, [Accessed: 8 October 2014].

2.4.3 European researchers in WWBRs

European researchers are international leaders in WWBRs. Some of their progress is summarised in the paragraphs below.

Marc van Loosdrecht's group at TU Delft works on biofilms and granular sludge systems, microbial storage polymers, nutrient removal processes and the microbial ecology of engineered systems. The development of the aerobic granular sludge system, commercialised as the Nereda®, is instrumental in widening possibilities for WWBRs. One publicised example of this is the pilot plant operating in the

Netherlands, producing PHA from chocolate wastewater (http://delta.tudelft.nl/artikel/living-on-water-from-mars/26740).

Jean Phillipe Steyer of the INRA, France, works on anaerobic digestion of algae (http://www.inra.fr/en/Partners-and-Agribusiness/Results-Innovations-Transfer/All-the-news/The-Algotron).

Frank Rogella, Aqualia's Innovation and Technology director in Madrid, works on high-rate algal treatment systems with biofuels as co-products. He leads a consortium, All-Gas, which was awarded one of the large projects of the European Union to demonstrate "algae to biofuel" implementation on a scale of 10 ha. The consortium maintains that the costs of its plant are well below those of a conventional system (http://www.reuters.com/article/2013/06/26/us-spain-bioenergy-idUSBRE95P0JG20130626; http://www.futureenergyevents.com/algae/2011/04/19/speaker-profile-frank-rogalla-director-of-innovation-and-technology-aqualia-gestion-integral-del-agua-s-a/).

Jose Porro is a senior researcher at Universitat de Girona, Madrid, Spain, who serves as a consultant for Arcadis in New York City. He is interested in sustainable and integrated urban water design, and currently doing his PhD at Ghent, where he is developing qualitative models for risk assessment of biological operational problems in urban water systems (http://www.sanitas-itn.eu/project/fellows/#ER1; http://modeleau.fsg.ulaval.ca/no_cache/en/people/phd_students/phd_students_details/professeur/140/2166/; http://www.novedar.com/ecoSTP/programme-plenaries.asp).

In the field of wetlands, Polprasert, Kadlec and Rittman are global leaders. *Dr Bruce Rittmann* is director of the Swette Center for Environmental Biotechnology at Arizona State University. He approaches environmental biotechnology from the perspective of "managing microbial communities that provide services to society. The concept of wastes or waste products is obsolete – the focus and the future are used resource recovery." This is achieved through cross-disciplinary and team-based research in the areas of engineering, science, sustainability, and biological design. Research topics include fundamental studies and practical applications such as microbial electrochemical cells, microbial photobioenergy and bioremediation. To make "research meet practice," Dr Rittmann's research teams integrate microbial ecology, chemistry and process kinetics through mathematical modelling, and they regularly collaborate with practitioners (http://rittmann.environmentalbiotechnology.org/).

Chongrak Polprasert is based at the School of Biochemical Engineering and Technology, Sirindhorn International Institute of Technology, Thailand. His research foci include water pollution control, waste recycling and recovery, and hazardous wastes engineering and management. He authored "Organic waste recycling: Technology and management" (Polprasert, 2007). Among others, he co-authored two articles that could contribute to WWBRs: "Phosphorus recovery from human urine and anaerobically treated wastewater through pH adjustment and chemical precipitation" (Kemacheevakul, et al., 2011), and "Treating swine wastewater by integrating earthworms into constructed wetlands" (Nuengjamnong, et al., 2011) (http://www.siitthailand.com/web/professor_en.php?id=32).

2.5 The South African WRC and WWBRs

The WRC of South Africa is the custodian of a large body of research into water and wastewater. This research was analysed to position the potential for the valorization of wastewater by using the WWBR concept. Reports commissioned by the WRC were reviewed. In the following two sections, research from academic institutions (Section 2.6) and trade literature (Section 2.7) is similarly reviewed, bringing together already existing knowledge and skills in South Africa while identifying knowledge and skills gaps.

A list of all reports from 1984 to 2015 was obtained from the WRC, totalling 2274 documents. Of these, 252 reports were deemed relevant to WWBR and were grouped into six main categories (Table 4; Figure 3). Where appropriate, these were further divided into more specific sub-categories. These are discussed below and the most promising reports highlighted in each category.

The reports are listed in Appendix **Error! Reference source not found.** and sorted into the six categories and further by year of publication.

Table 4: Number of WRC reports relevant to WWBR in each of six categories

Category	Number of reports in category	Percent
A. Wastewater management	112	43.1%
B. Wastewater treatment technology	89	34.2%
C. Cleaner production	14	5.4%
D. Products from wastewater	18	6.9%
E. Products to be used in wastewater	16	6.2%
F. WWBRs	11	4.2%
Total	**260**	

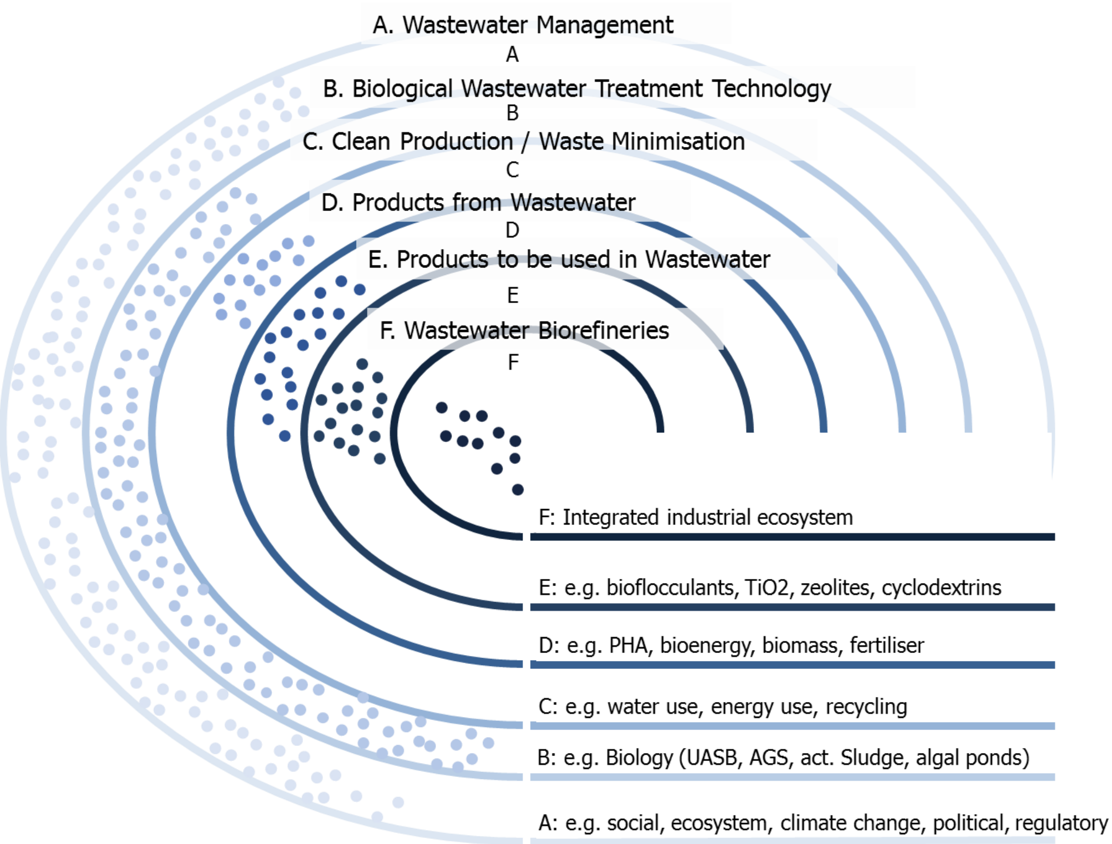


*Figure 3: Graphical illustration of the context of WWBR-related research listed in Appendix **Error! Reference source not found.***

2.5.1 Category A: Wastewater management

Almost half of the relevant reports dealt with managing wastewater. This reflects thinking from about 2005 onwards and suggests that this is may be the most challenging part of WWBR. The demand-side of water resource management focuses attention on how to manage water demand and use. This shift is influenced to an extent by various social advocacy movements, but is also influenced by increasing recognition of resource scarcity, heightened interest in sustainable development considerations, post-modern philosophies and increased prominence of environmental justice, equity and democratisation of resources (Siebrits, et al., 2014).

The classification of the reports on wastewater management is given in Table 5. Some highlights of the general reports in category A are listed in Table 6 to illustrate the type of projects undertaken.

Table 5: Number of WRC reports relevant to WWBR regarding wastewater management (Category A) in each of six sub-categories

Category A: Wastewater Management	Number of Reports in Sub-category	Percentage of Category A
1. General	40	35.7%
2. Analysis and characterisation	12	10.7%
3. Health	9	8.0%
4. Meta-research	22	19.7%
5. Economics	18	16.1%
6. Solids: Landfill and rural	11	9.8%
Total	**112**	

Table 6: Most relevant WRC reports from Category A: Wastewater management

Title	Year of pub.	Value of research	Gaps/further research required for application to WWBR
2085/1/14: Mitchell SA, De Wit MP, Blignaut JN, Crookes D, "Waste water treatment plants: The financing mechanisms associated with achieving Green Drop rating"	2014	Financing mechanisms of wastewater treatment plants.	Improve the performance of WWTWs by providing an incentive to the works in the form of a scoring system. Limited applicability to WWBR, except as an operational incentive mechanism.
TT 588/13: Armitage N, Fisher-Jeffes L, Carden K, Winter K, Naidoo V, Spiegel A, Mauck B, Coulson D, "Water sensitive urban design (WSUD) for South Africa: Framework and guidelines"	2014	Biological and chemical treatment of associated contaminants, drainage and the management of industrial effluents. Water-energy-food nexus. Wastewater reuse and minimisation.	Big picture of WWBR and beyond.
TT 564/13: Wall K, Ive O, "Social franchising partnerships for operation and maintenance of water services: Lessons and experiences from an Eastern Cape pilot"	2013	An investigation of the business model that could occur in the sanitation sector.	The project is aimed at a more social responsiveness and community level. It would be interesting to see if this can be extended to a bioproduction facility context.
TT 518/12: Schulze RE, "A 2011 perspective on climate change and the South African water sector"	2011	The effect of climate change on hydrological responses. Predictive scenarios, indicating risk levels, for the biophysical changes associated with projected climatic change for climatically divergent catchments in South Africa were then developed.	Could be placed into context of WWBR and how WWBR contributes to mitigating climate change and builds resilience.

Analysis and characterisation

Reports dealing with analysis and characterisation of wastewaters are important to this project, but most of these were published more than five years ago. Of particular interest are techniques that can be used to analyse the more complex requirements regarding the composition of a WWBR stream. The most notable of the existing reports are listed in Table 7.

Table 7: Most relevant WRC reports from Category A.2: Analysis techniques that may be useful in WWBR

Title	Year of pub.	Value of research	Gaps/Further research required for application to WWBR
KV 249/10: Garcin CJ, Nicolls F, Randall B, Fraser M, Griffiths M, Harrison STL, "Development of LED-photodiode-flow cell for online measurement of dissolved substances in liquids"	2010		WWBR process control and analysis
TT 405/09: Leopold P, Freese SD, "A simple guide to the chemistry, selection and use of chemicals for water and wastewater treatment"	2009		
1286/1/07: Pillay B, Dechlan, "Development and application of prokaryotic biosensor systems for the evaluation of toxicity of environmental water samples"	2007		Potential way to evaluate incoming wastewater to prevent system failure

Meta-research

Meta-research reports are of primary importance in this study because of the need to position this research in the current South Africa wastewater management setting. Further, meta-research is a key resource at the start of any focused project for accessing introductory information quickly, and for locating the initial material for more specific investigation. Some of the more helpful overview reports are listed in Table 8.

Table 8: Most relevant WRC reports from Category A.4: Meta-research reports

Title	Year of pub.	Value of research	Gaps/further research required for application to WWBR
2199/1/12: Pouris A, "A pulse study on the state of water research and development in South Africa"	2012	A quantitative account of key R&D trends in the water sector. The analysis identifies that the field is performing above expectation in comparison with the country's research size.	Overview of the research landscape in South Africa regarding water. However, little attention has been given to the increasingly important water reuse/recovery/beneficiation concepts.
TT 514/11: Claassen M, Funke N, Nienaber S, "The water sector institutional landscape by 2025"	2011	Project to build knowledge about key drivers and uncertainties related to South African water sector institutions, with a focus on water resource management.	WWBRs can feed into water resource management as a water source, thus this report outlines some key stakeholders in the space.
1547/1/10: Cloete TE, Gerber A, Maritz L, "Inventory of water use and waste production by industry, mining and electricity generation"	2010	The overall objective of this project was to compile a first-order inventory of the amount of water used and effluent produced by the South African industrial, mining and power generation sectors, and to assess the impact these might have on water quality, but existing data sets were of limited value and outdated.	Much of the data is out of date, and some data is inconsistent. It is of great concern that many of the surveyed industries do not conduct any chemical analyses on the effluents that they produce and that where chemical analyses are done, they very seldom go beyond a few basic parameters such as chemical oxygen demand (COD), phosphate and nitrate.

Solid waste management

Reports dealing with solids were of particular interest, as the first objective of product recovery is decoupling solid and liquid residence time. As this report is concerned with the more technical aspects of WWBR, the distinction of solids was used rather than rural (vs urban), or sewered vs non-sewered. The most relevant reports are given in Table 9.

Table 9: Most relevant WRC reports from Category A.6: Solid waste management relating to wastewater

Title	Year of pub.	Value of research	Gaps/FURTHER research required for application to WWBR
1240/1/04: Marx CJ, Alexander WV, Johannes WG, Steinbach-Kane S, "A technical and financial review of sludge treatment technologies"	2004	The aim was to give a clear indication to metropolitan councils, municipalities and other sludge producers of the technologies available and applicable under local conditions, as well as an indication of the cost and economy of scale applicable to each process. The study includes an overview of current sludge management practices in South Africa, an estimate of sludge quantities and qualities, and a brief description of commonly used sludge treatment and disposal methods.	Applicable to sludges used/produced in WWBR, including the legal framework, using as a basis the sludge utilisation or disposal decision flow diagram, as presented in the Addendum No. 1 to the Permissible Utilisation and Disposal of Sewage Sludge (Edition 1), (Department of Agriculture et al., 1997).
TT 107/99: Ceronio AD, Van Vuuren LRJ, Warner APC, "Guidelines for the design and operation of sewage sludge drying beds"	1999	Sludge drying/'preprocessing'	Needs further work to consider drying beds as solid substrate bioreactors.

2.5.2 Category B: Wastewater treatment technology

The 81 WRC reports relevant to WWBR regarding wastewater treatment technology, Category B, were further grouped into nine sub-categories considering specific unit technologies (Table 10).

Table 10: Number of WRC reports relevant to WWBR regarding wastewater treatment technology (Category B), in each of nine sub-categories

Category B: Wastewater Treatment Technology	Number of Reports in Sub-category	Percent of Category B
1. General	42	47.2%
2. Anaerobic digestion	7	7.9%
3. Biological nutrient removal (BNR)	5	5.6%
4. Algae	1	1.1%
5. Wetland	4	4.5%
6. Membrane	18	20.2%
7. Solid substrate fermentation (SSF)	7	7.9%
8. Nanotechnology	3	3.4%
9. Upflow anaerobic sludge blanket (UASB)	2	2.2%
Total	**89**	

In this category, reports detailing reactor technology that can deal with solid substrate were of particular interest, and are listed in Table 11. It is pertinent to develop WWBR technologies and feasible business models that focus on solid wastes because of the large number of non-sewered disposal routes, particularly in developing countries. Further, the first step in a WWBR is to decouple the solid and liquid residence times, which necessitates specific consideration of the solids component.

Table 11: Most relevant WRC reports from Category B.7: Solid waste reactor technology relating to wastewater

Title	Year of pub.	Value of research	Gaps/further research required for application to WWBR
766/1/05: De Jesus AE, Heinze PH, Muller JR, Nortje GL, "Utilisation of earthworms and associated systems for the treatment of effluent from red meat abattoirs"	2005	Utilisation of earthworms and associated systems to treat effluent from red meat abattoirs.	Use of vermicompost or vermiculture for pretreatment of biosolids before the biosolids reactor.
1129/1/04: Burton SG, Ryan DR, Van Wyk L, "Bioreactor systems using the white rot fungus Trametes for bioremediation of industrial wastewater"	2004	Immobilised biofilm reactors in the form of a transverse flow membrane bioreactor and a trickle bed reactor were identified as suitable for growth, enzyme production and phenolic removal by *Tenia versicolor*.	Investigate the value of this work in context of WWBR – does it optimise well as a unit process in the treatment train? Take the system to larger scale and demonstrate its effectiveness at pilot scale.
333/1/97: Whyte DC, Swartz CD, "The removal of suspended solids from pulp and paper effluents by employing the combined sedimentation flotation process"	1997	The most significant conclusions of this study are that high percentages of removal for suspended solids can be obtained with the combined SEDIDAF process; the settling stage of the process contributes most to the overall removal of solids from the effluent.	Investigate the application potential for WWBR. Has this been applied to industry since publication of this report?

2.5.3 Category C: Cleaner production

Cleaner production is the precursor to WWBRs and, as such, is important to consider as a category. The key reports in this area are listed in Table 12. Important work has been done in this field, notably by Prof. Chris Buckley at the Pollution Research Group at the University of KwaZulu-Natal (UKZN).

Table 12: Most relevant WRC reports in Category C: Cleaner production

Title	Year of pub.	Value of research	Gaps/further research required for application to WWBR
TT 546/12: Mvuma GG, Hooijman F, Brent AC, Oelofse SHH, Rogers DEC, "Volume III: Development and assessment of technological interventions for cleaner production at the scale of the complex"	2012	Key factors that influence the environmental sustainability of a large inland industrial complex: The Secunda Industrial Complex.	Assessment of cleaner production options and environmental assessment by life cycle analysis (LCA).
1625/1/08: Majozi T, Gouws JF, "Development of a complete process integration framework for wastewater minimisation in multipurpose batch plants"	2008		Important thinking for WWBR.
TT 283 & 4/07: Barclay S, Buckley C, "Waste minimisation clubs in South Africa (facilitation and training manual)"	2007	Cleaner production initiative.	

2.5.4 Category D: Products from wastewater

Products that can be produced from wastewater depend on the ecological advantage the product gives to the organisms producing it. It is also crucial to consider the market needs, ensuring that the market can absorb products from the wastewater. To maintain economic feasibility, the productivity needs to be high enough to cover operational costs. Category D contains WRC reports that address these aspects, and some highlighted reports are listed in Table 13.

Table 13: Most relevant WRC reports in Category D: Products from wastewater

Title	Year of pub.	Value of research	Gaps/further research required for application to WWBR
1724/1/12: Tesfamariam EH, Annandale JG, De Jager PC, Mbakwe I, Van der Merwe P, Nobela L, Van der Laan M, "Sustainable agricultural use of municipal wastewater sludge, 1724/2/12: The potential of sludge amended combustion coal ash residues"	2012	An investigation of using sludge (both municipal waste derived, and petrochemical waste derived) for agriculture.	Recovery and reuse of nitrogen and phosphorous from sludge for agriculture. More work needed on the requirements of processing that would allow the products to be considered, or acceptable for use as originating from sludge (more than just soil additive).
1937/1/11: Burton SG, Mupure CH, Horne KA, Jones S, Welz PJ, "Beneficiation of agri-industry effluents"	2011	Downstream processing (DSP) of agri-wastes for recovery of valuable products (phenols, antioxidants and sugars).	A closer evaluation of the (economic) feasibility and market potential of concepts highlighted in this study.
1367/1/05: Christopher L, "Bio-remediation and bio-utilisation of pulping and bleaching waste waters"	2005	This technical paper demonstrates the reduction of toxic chemical use when using alternative bleaches such as enzymatic approaches. Furthermore, valuable products (such as the above-mentioned enzymes) can be produced from the pulp wastewaters.	The application of the wastewater technology (cleaning pulp wastewater to produce enzymes) is applicable to WWBRs, more than the first part of the report.

2.5.5 Category E: Products to be used in wastewater treatment

Generating products that can be used in the treatment processes used to produce them are promising avenues to illustrate the WWBR concept without immediately needing to address broader logistical issues. This approach secures a market for the products.

The WRC reports in this category mostly evaluated specific products. It would be useful to research whether those effective products can be produced from the wastewater they are used to treat. Some highlights are listed in Table 14.

Table 14: Most relevant WRC reports in Category E: Products to be used in wastewater treatment

Title	Year of pub.	Value of research	Gaps/further research required for application to WWBR
KV 248/10: Lutchamma-Dudoo C, "Biologically enhanced primary settlement"	2010	Investigation into using biological agents as settling agents to replace the more commonly used ferric chloride, to allow rural communities to become more self-reliant regarding wastewater treatment.	The technology could be applied in WWBRs, although its capabilities and limitations need to be further explored.
1363/1/08: Binda M, Gounder P, Buckley CA, "Promotion of biodegradable chemicals in the textile industry"	2008	Development of a score system for textile industry effluent. A pilot study of implementing the score system at volunteer factories.	This methodology could be usefully applied to WWBRs for influent and effluent analysis. However, more work is required to apply the methodology to other industrial effluents.
1377/1/05: Taljaard L, Venter A, Gorton D, "An evaluation of different commercial microbial or microbially-derived products for the treatment of organic waste in pit latrines"	2005	Investigated the claims of 16 microbially-derived products for treating organic waste in pit latrines to speed up the process, control odour and reduce the bulk of organic material.	Results did not seem particularly promising. Designing pit latrines to promote their own healthy ecosystem may be better (ecological engineering).

2.5.6 Category F: Reports most closely associated with the WWBR concept

It was encouraging to see some work about integrating waste streams towards product recovery, paving the way to WWBR. These span a wide spectrum of thinking – from single unit product recovery to incorporating the societal impacts into the proposed beneficiation process. Highlights of the relevant reports are listed in Table 15.

Table 15: WRC reports most closely associated with WWBR

Title	Year of pub.	Value of research	Gaps/further research required for application to WWBR
1803/1/13: Blignaut J, De Wit M, Milton S, Esler K, Le Maitre D, Mitchell S, Crookes D, "A market for ecosystem goods and services following the restoration of natural capital: Volume 1: Main report" (and 1803/2/13)	2013	Integrated system dynamics model on the likely impact of restoration on the ecology, hydrology and economy of restoration sites.	Ecosystem economics possibly applicable to WWBR, although products are not the focus of the model.
TT 399/09: Burton SG, Cohen B, Harrison S, Pather–Elias S, Stafford W, Van Hille R, Von Blottnitz H, "Energy from wastewater: A feasibility study (essence report)"	2009	An overview of the chemical potential of wastewater, making WWBRs possible in principle.	Only considers energy products. Similar work is required for commodity chemicals, and nitrogen- and phosphate-containing products.
TT 235/04: Rouhani QA, Britz PJ, "Contribution of aquaculture to rural livelihoods in South Africa: A baseline study"	2004	Contribution of aquaculture to rural livelihoods in South Africa: A baseline study.	Should aquaculture be considered in WWBR?
1081/1/04: Klusener CW, "The development of a protein recovery technology at Sezela for the treatment of furfural plant azeotrope effluent with the simultaneous production of mycoprotein"	2004	Production of bioproduct furfural.	Treating industrial effluent and generating income from it. Good example of WWBR.
1082/1/03: Christof LP, "Further development of a biotechnological approach to the management of waste waters from the pulp and paper industry"	2003	Managing wastewater from pulp and paper industry for subsequent production of bioproducts.	Developing more environmental friendly processes to treat wastewater and the use of microorganisms to produce valuable products such as single-cell protein and high-value fatty acids.
939/1/03: Burton SG, Boshoff A, Foster I, Koteshwar K, Luke A, Mhlanga C, Nganwa P, Notshe T, Ryan D, "Bioreactor systems for the conversion of organic compounds in industrial effluents to useful products"	2003	Value recovery from industrial effluent.	A techno-economic analysis needs to be done.
TT 187/02: Rose PD, "Salinity, sanitation and sustainability: A study in environmental biotechnology and integrated wastewater beneficiation in South Africa (Report 1)" (and TT 188/02, TT 190/02, TT 191/02, TT 192/02, TT 196/02, TT 409/09)	2002	The BioSure process considers the treatment of acid mine drainage using sewage sludge as electron donor. Potential exist to recover a sulphur product (and metals).	A short explicit value offering would be a better "marketing tool".
1054/1/01: Abbott G, "Cultivation of high-value aquatic plants in restored urban wetlands for income generation in local communities ('new green' database)"	2001	Considering wetland plants as value-added products.	More thinking about wetlands as macrophyte bioreactors, and looking at the system as a whole.

2.6 South African Academic Institutions and WWBRs

2.6.1 South African academic research groups with WWBR themes

A search was conducted to identify the academic groups in South Africa studying the recovery of value from wastewaters. The annual reports of the various universities, "The state of waste to energy research in South Africa: A review" (SANEDI, 2014), "The state of energy research in South Africa" (ASSAf, 2014), and internet-based searches were conducted to explore the various role players in the water and wastewater research space (Table 16). This listing of research groups is not intended to be a comprehensive list, but rather the start of exploring the work currently being done in the area. While every care has been taken to include relevant research, there may be groups that have been missed. A necessary outcome may to create a database that allows users to update their own information.

Table 16: South African academic researchers in the water and wastewater sphere

Institute	Name	Directors/lead investigators	Projects/themes relevant to WWBR	Reference
UCT	Centre for Bioprocess Engineering Research (CeBER), Dept. Chemical Engineering	Prof. Sue Harrison; Dr Madelyn Johnstone-Robertson; Dr Rob Huddy	CeBER strives to address environmental issues primarily related to water, with consideration of the potential for value add. Current projects consider acid rock drainage, prevention through enhanced management and use of waste materials and remediation, using biological sulphate reduction and sulphide oxidation technologies for acid rock drainage treatment, biological cyanide degradation, anaerobic digestion, algal processes, metal removal and the remediation of olive-processing wastewaters. Across these projects there is a focus on integrated systems, microbial ecology and the potential for value recovery. At the macro-scale, CeBER has expertise in sustainability and LCAs and emerging technologies for renewable energy generation and greenhouse gas (GHG) emission reductions.	http://www.ceber.uct.ac.za/index.php?option=com_k2&view=item&id=10:green-biotechnology&Itemid=29
UCT	Water Research Group, Dept. of Civil Engineering	Prof. George Ekama; Dr David Ikumi	Research focuses mainly on environmental systems engineering, which seeks to develop an understanding of the fundamental chemical, physical and biological processes operating in various water-related systems, such as water storage (impoundments), transport (rivers, pipes, sewers) and treatment plants (potable and wastewater).	http://www.civil.uct.ac.za/water-research-group
UCT	Urban Water Management Research Unit	Prof. Neil Armitage; Dr Kirsty Carden	• Urban water services. • Water-sensitive urban design. • Sanitation in informal settlements.	http://www.civil.uct.ac.za/associate-professor-neil-armitage#sthash.khZoSSFN.dpu http://www.civil.uct.ac.za/associate-professor-neil-armitage
UCT	Environmental and Geographical Science	Dr Kevin Winter	• Water quality monitoring. • Public/government partnerships. • Informal settlement upgrading.	http://www.ddrn.dk/filer/forum/File/Overview_Report_UEM_Southern_%20Africa_February_2008.pdf http://www.egs.uct.ac.za/staff_files/kevin.html
Rhodes University	Institute for Water Research (IWR) incorporating the Unilever Centre for Environmental Water Quality (UCEWQ)	Prof. Dennis Hughes (IWR) and Prof. Carolyn Palmer (UCEWQ)	• Hydrology project. • Environmental water quality projects. • Water Resource Management projects.	http://www.ru.ac.za/static/institutes/iwr/ http://www.ru.ac.za/static/institutes/iwr/publications/IWRAnnualReport2011.pdf
Rhodes University	Biotechnology Innovation Centre	Prof. Janice Limson	Remediation of wastewater coupled to power generation in microbial fuels.	http://www.ru.ac.za/biotech/people/staff/profjanicelimson/ SANEDI (2014) report

Institute	Name	Directors/lead investigators	Projects/themes relevant to WWBR	Reference
Rhodes University		Prof. Brett Pletschke	Immobilisation of enzymes onto nanofibers for subsequent application in water/wastewater research.	http://www.ru.ac.za/bm/people/academicstaff/pletschke/research/#d.en.35053
Rhodes University	Institute for Environmental Biotechnology (EBRU)	Prof. Keith Cowan	The research focus of EBRU has targeted the advancement of sustainability through remediation and the beneficiation of saline, domestic and industrial wastewater for high-value products and biofuels, and the exploitation of solid waste for use in agriculture and industry. Projects investigating value addition are actively pursued and included in this portfolio: • Integrated algae ponding systems for treating organic effluents and generating a treated water that is safe for discharge into the environment. • Recovering commercially valuable metabolites e.g. β-carotene, glycerol and fertiliser from microalgae. • Exploring the potential of microalgae biomass as a feedstock for renewable energy production. • Treating mine drainage wastewaters and using this in agro-industrial development as a basis for social, economic and environmental sustainability, especially applicable following mine closure. • Removing heavy metals from the environment using biological systems. • Using South African hardwood fungi to bioremediate coal and hydrocarbon wastes.	http://www.ru.ac.za/ebru/aboutebru/
UKZN	Pollution Research Group	Prof. Chris Buckley	The group's main focus is conducting innovative research projects on water resources, wastewater reclamation, the impact of effluents on local environments, sanitation systems, and other water-related environmental issues. The group has completed many projects commissioned by the WRC relating to wastewater topics potentially relevant to WWBR. Current projects include (among others): • Co-digestion of sewage sludge and industrial concentrates (WRC K5/2001). • Integration of aquatic chemistry with bioprocess models (WRC K5/2125). • Integrating agriculture in designing low cost sanitation technologies (WRC K5/2220). • Micro-nutrient requirements for anaerobic digestion of concentrated industrial effluents (WRC K5/2228). • Water and waste water management in the soft drink industry (WRC K5/2286). • Development of an aerobic membrane bioreactor for treating Illovo wastewater (funded by Illovo).	http://prg.ukzn.ac.za/ http://prg.ukzn.ac.za/home http://prg.ukzn.ac.za/projects
UKZN	Centre for Research in Environmental, Coastal and Hydrological Engineering	Prof. Christina Trois	• Wastewater management. • Wastewater treatment. • Renewable energy from waste. • GHG control from zero waste.	ASSAF (2014) report http://civeng.ukzn.ac.za/Research.aspx
UKZN	Water, Environment and Biodiversity	Various researchers from UKZN	• Hydrology. • Waste, water and sanitation management. • Micrometeorology and agrometeorology. • Hydrological engineering. • Limnology. • The Smallholder System Innovations research project.	http://research.ukzn.ac.za/ResearchFocusAreas/WaterEnvironmentand Biodiversity.aspx
University of Stellenbosch	Water Institute (involving several departments)	Prof. Gideon Wolfaardt (Director) Prof. Eugene Cloete (Chairperson)	• Effluent management. • Nanotechnology and filtration. • Sustainable water management. • Water and agriculture. • Water and food. • Water and health. • Water and society.	http://water.sun.ac.za/

Institute	Name	Directors/lead investigators	Projects/themes relevant to WWBR	Reference
North-West University	School of Chemical and Minerals Engineering, Potchefstroom Campus	Prof. Sanette Marx	Membrane technology	http://www.nwu.ac.za/sites/www.nwu.ac.za/files/files/pfe/documents/cv/Prof.%20S.%20Marx%20-%20Associate%20Professor.pdf
University of Pretoria	Chemical Engineering Biochemical Engineering Water Utilisation	Dr Willie Nicol Prof. Evans Chirwa	Bioreactors (biofilm and membrane-recycle bioreactor).	http://www.up.ac.za/chemical-engineering/article/1913314/bioreaction-engineering http://www.up.ac.za/chemical-engineering/article/1913286/biochemical-engineering http://www.up.ac.za/chemical-engineering/article/1913292/water-utilisation
Durban University of Technology	Institute for Water and Wastewater Technology (IWWT)	Prof. Faizal Bux Dr Sheana Kumari Dr N Ramdhani	The focus is largely based on developing and optimising technology for treating water and wastewater and satisfying the needs of industry and the community. Projects are mainly aimed at helping industries to maintain acceptable levels of effluent discharges, thus reducing negative environmental impact and commercialisation of products generated from waste streams.	http://www.dut.ac.za/iwwt SANEDI (2014) report ASSAf (2014) report
Vaal University of Technology	Centre for Renewable Energy and Water, Chemical Engineering Department	Prof. Ochieng Aoyi	• Application of adsorption technique in point-of-use potable water purification and in wastewater remediation. • Storm water management and hydrology. • Biological wastewater treatment and environmental pollution control. • Application of computational fluid dynamics technique in reactor optimisation. • Application of nanomaterials in pollution management.	SANEDI (2014) report http://www.vut-research.ac.za/index.php/higher-degrees/higher-degrees-studies/payment-options/44-vut/research/179-water-and-bioenergy-centre
Tshwane University of Technology	Department of Environmental, Water and Earth Sciences	Prof. Maggie Momba	Various aspects of water with emphasis on water and wastewater management, health, related water microbiology, biotechnology and molecular biology.	http://www.tut.ac.za/Students/faculties departments/science/departments/environscience/Documents/Maggie%20Momba%20Simple%20removed%20photos.pdf
Cape Peninsula University of Technology (CPUT)	Biocatalysis and Technical Biology Research Group	Dr Marilize le Roes-Hill	The main focus of the research group centres on the discovery and use of robust industrial biocatalysts in applications that range from bioremediation of industrial wastewater to antioxidant synthesis. The research areas range over enzyme discovery, enzyme mutation studies and actinobacteria biology to bioreactor design for wastewater treatment.	http://www.cput.ac.za/files/images_folder/researchdictorate/Research%20Report%202011%20smaller.pdf
CPUT	Biotechnology and Water Treatment	Prof. Marshal Sheldon	• Colour removal from textile wastewater using a pilot-scale dual-stage membrane reactor (MBR) and subsequent reverse osmosis system • Water reuse using a dual-stage membrane bioreactor for industrial effluent treatment. • Membrane bioreactor application within the treatment of high-strength textile effluent. • Treatment of paper mill effluent using an anaerobic/aerobic hybrid side-stream membrane bioreactor.	http://www.cput.ac.za/files/images_folder/researchdictorate/Research%20Report%202011%20smaller.pdf

2.6.2 *Journal articles with WWBR themes published by South African researchers*

The Elsevier abstract and citation database of peer-reviewed literature, Scopus (Elsevier, n.d.), was used to discover journal articles in the international literature published by South African scientists and engineers. The keywords "wastewater treatment" with "South Africa" as affiliate delivered 924 articles, which is a very broad base of research. However, "value from wastewater" with "South Africa" as affiliate yielded a much narrower 165 entries. The final selection for further scrutiny was made using the keywords "water, wastewater, effluent, industrial" and "South Africa" as affiliate. This search produced 124 publications spanning 1978 to 2015. These publications were further analysed and reduced to the 48 most relevant articles (see Appendix **Error! Reference source not found.**). Using the same approach as in Section 2.5, these references were classified into Categories A-F, represented graphically in Figure 4. Most research focused on Category B at 47.9%, with Category D and Category E 14.6% each, Category C 10.4%, and Category F and Category A 6.25% each.

Table 17: Number of journal articles with WWBR themes by South African researchers in each of six categories

Category	Number of reports in category	Percent
A. Wastewater management	3	6.25%
B. Wastewater treatment technology	23	47.9%
C. Cleaner production	5	10.4%
D. Products from wastewater	7	14.6%
E. Products to be used in wastewater	7	14.6%
F. WWBRs	3	6.25%
Total	48	

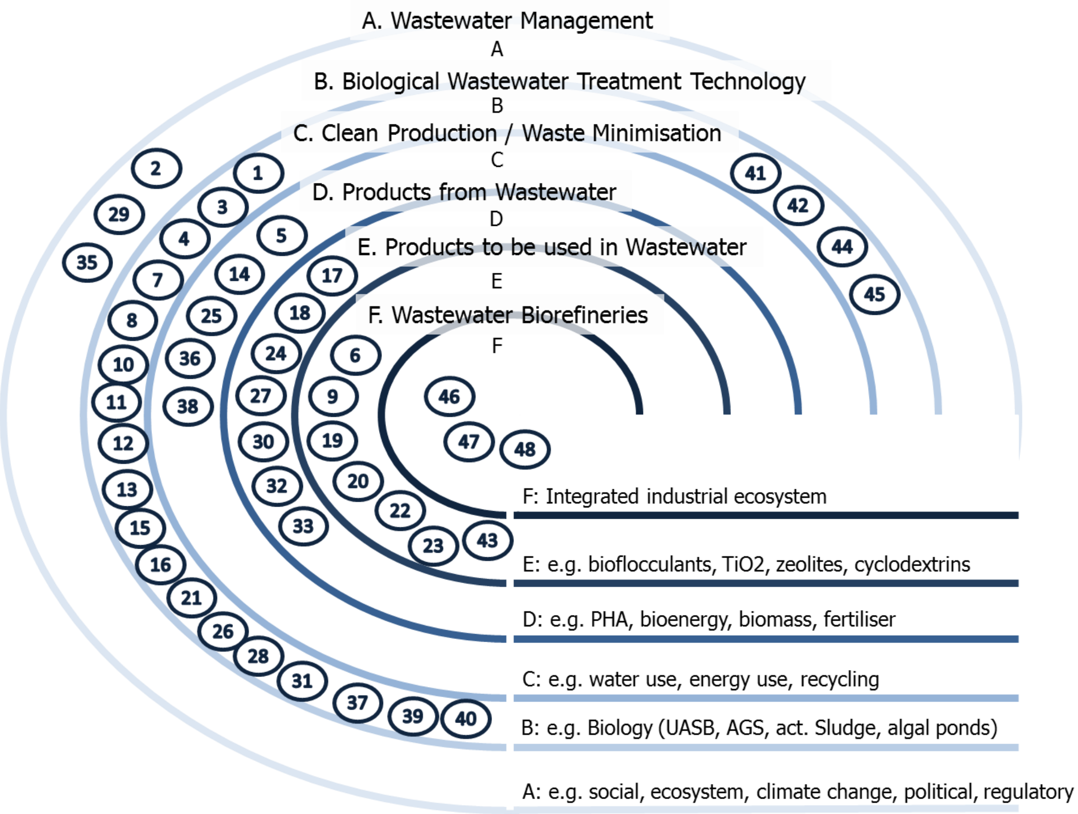


*Figure 4: Graphical illustration of the context of WWBRs related to South African research published in journals (listed in Appendix **Error! Reference source not found.**)*

Pitman and Boyd (number 29 in **Error! Reference source not found.** (1999)) mentioned the need to remove nutrients from wastewater by biological means and to dispose of the sludge by-products in an efficient manner. This prompted the Greater Johannesburg Metropolitan Council to adopt a new approach to managing industrial discharges. This is encouraging as it indicates that academic research can and does enable changes in the wastewater industry. The role of the Rand Water research in facilitating this interaction between new knowledge and implementation should be explored.

The Scopus search was refined using "wastewater biorefinery" and "South Africa" as affiliate as keywords, giving three entries, all from the group of Prof. Faizal Bux (IWWT) at Durban University of Technology (DUT). The three entries are listed in Table 18 and as references 46 (Singh, et al., 2015), 47 (Rawat, et al., 2013), and 48 (Rawat, et al., 2011) (Appendix **Error! Reference source not found.**). These articles explore the biorefinery approach using wastewater as an algal production medium for CO_2 capture from flue gas to grow algae to produce biodiesel, other biofuels and value-added products, and offering environmental protection.

Table 18: South African research published in peer-reviewed journals Sourced through Scopus using the keywords "wastewater biorefinery" and "South Africa" (extract from table in Appendix ***Error! Reference source not found.****)*

	Authors	Affiliation	Title of journal paper	Year of pub	Journal	Value of research in context of WWBRs
46	Singh, B., Guldh, A., Singh, P., Rawat, I., Bux, F., Singh, A.	Centre for Environmental Sciences, Central University of Jharkhand, Ranchi, India and IWWT, DUT	Sustainable production of biofuels from microalgae using a biorefinery approach	2015	Applied Environmental Biotechnology: Present Scenario and Future Trends, Springer, New Delhi, 115-128	The value-added product derived from biorefinery basket includes pigments, nutraceuticals, and bioactive compounds. The use of industrial refusals for biomass production includes wastewater as nutrient medium and utilisation of flue gases (CO_2) as the carbon source for culture of microalgae. These processes have the potential to reduce the freshwater and carbon footprint.
47	Rawat, I., Bhola, V., Kumar, R.R., Bux, F.	IWWT, DUT	Improving the feasibility of producing biofuels from microalgae using wastewater	2013	Environmental Technology, 34 (13-14), pp. 1765-1775	The use of a biorefinery approach sees the production costs reduced greatly due to the use of waste streams for cultivation and the generation of several potential energy sources and value-added products while offering environmental protection. The use of wastewater as a production medium coupled with CO_2 capture from flue gas greatly reduces the microalgal cultivation costs. Conversion of residual biomass and by-products, such as glycerol, for fuel production using an integrated approach potentially holds the key to near future commercial implementation of biofuels production.
48	Rawat, I., Ranjith Kumar, R., Mutanda, T., Bux, F.	IWWT, DUT	Dual role of microalgae: Phycoremediation of domestic wastewater and biomass production for sustainable biofuels production	2011	Applied Energy, 88 (10), pp. 3411-3424	This paper discusses current knowledge regarding wastewater treatment using (high-rate algal ponds) HRAPs and microalgal biomass production techniques using wastewater streams. The paper discusses biodiesel production via transesterification of the lipids and other biofuels such as biomethane and bioethanol, which are described using the biorefinery approach.

2.7 South African Industry-Based Initiatives in the WWBR Arena

An attempt was made to determine the current state of industry-based initiatives relating to WWBR in South Africa. However, determining the state of wastewater resource recovery in South African industry proved challenging. The search specifically excluded wastewater treatment without value-generating products, and only considered treatment that uses biobased technology. The following steps were taken in exploring the status of industry-based initiatives:

- Web-based searches were conducted using several keywords and following anecdotal leads.
- Industry professionals in South Africa were contacted, drawn from the networks of the research team (see Acknowledgements).

- Members of the WRC project Reference Group were contacted (see Acknowledgements).

In spite of considerable effort, a rigorous review of the value-from-wastewater space in South Africa was found to be out of reach. Much of the information related to client-confidential projects, so that contacts were unable to divulge full details. The information available was largely derived from quasi-technical news-related articles promoting the environmental awareness of the entity in question.

There are some organisations reporting in this arena, and the reports and groupings which were found to be helpful are enumerated. Information relating to industrial wastewater, municipal wastewater, technology development and service providers is given, focusing on a single project in each case. Finally, some brief conclusions are drawn.

2.7.1 Overview reports and organisations

There are a number of reports germane to the current levels of industrial implementation of WWBR-relevant technology. At a global level, these give helpful insights in terms of placing South Africa within the global framework of concern about water security.

- Carbon Disclosure Project (CDP) Global Water Report 2015 (CDP, 2015).
- IWA Resource Recovery from Water, 2015 (IWA Resource Recovery Cluster, 2015).

The Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) is involved in a number of high-level reports with other (South African) organisations such as the South African National Energy institute (SANEDI), Renewable Energy Centre of Research and Development (RECORD) and the South African Local Government Association (SALGA).

- "The state of waste to energy research in South Africa", August 2014 (GIZ, RECORD & SANEDI, 2014).
- "Biogas potential in selected waste water treatment plants", March 2015 (Ferry & Giljova, 2015).

The Strategic Water Partners Network (SWPN, 2013; 2015) has more than 20 partners, but their publications are mostly rhetoric at this stage.

The South African Biogas Industry Association (SABIA) is a relatively new grouping relevant to biogas within the WWBR. Since biogas is the dominant product currently produced from wastewater in South Africa, this information is helpful.

GreenCape was established in 2010 as a regional resource centre in the Western Cape. They provide useful regional insight regarding aspects of the "green economy". There may be similar organisations in other regions.

2.7.2 Industrial wastewater

A selection of examples of industrial wastewater approaches are given in this section.

SABMiller, with seven breweries in South Africa, has committed itself to "working towards zero waste operations" (SAB, 2013). This places it firmly in the area of application for opportunities presented by the WWBR concept (see Section 2.2.1 and Section 2.3). In 2009, four breweries (Burton, et al., 2009; SAB, n.d.) had anaerobic digestion wastewater facilities producing biogas used as an energy source in the brewing process. Up until ten years ago, the biogas from these units was flared at all units (Burton, et al., 2009), so the value recovery aspect is fairly recent. The Newlands Brewery, Western Cape, has sponsored at least two postgraduate research projects at UCT (Cohen, 2006; Nkadimeng, 2015) assessing opportunities in biogas production and use. Their biogas is used to power their steam boiler, allowing substantial electricity savings to be accrued. "Currently, the steam generated … accounts for around 10% to 12% of the total steam required in the brewing process with the balance generated from electricity" (Nkadimeng, 2015).

The iBhayi Brewery, Eastern Cape, partnered with Rhodes University and two organisations based in India to expand this approach to wastewater. HRAP and constructed wetland technology are used in addition to anaerobic digestion. The system produces hydroponic lettuce and fish (Crous & Britz, 2010; SAB, n.d.; SAB, 2014). The wetland uses considerable portions of land, which means that the technology is not transferable to all sites (Seggie, 2011). The treated water remains saline and can only be released into naturally saline waterbodies such as estuaries (Seggie, 2011). The use of multi-stage processing together with the production of several products (biogas, fish and lettuce) places this system close to the WWBR concept.

Since brewing is already a biological process, it is appropriate that the brewing industry be an early adopter of biological wastewater treatment; therefore, it has good potential as a frontrunner for the WWBR. In essence, this move would make the brewery into a biorefinery *per se*, where the initial feedstock is not a wastewater stream but the subsequent (bio)processes produce value-added products downstream of the brewing.

There are several other industries with customised wastewater processes in South Africa. The pulp and paper industry is water-intensive and invests considerable resources in wastewater treatment (Ndaba, 2011; SAPPI, 2014). Currently, it seems that the only value recovery across most of the industry is in reusing treated water to reduce the overall water footprint (Macdonald, 2004). At least three companies in the petrochemical industry are known to have invested heavily in wastewater treatment. Chevron Refinery, Western Cape, uses a moving bed bioreactor followed by clarifying steps before reuse (Chevron, n.d.; Petroleum Africa, 2008; Veolia, n.d.-a). The South African Petroleum Refineries (SAPREF) in Durban, KwaZulu-Natal, uses recycled water from the Durban Water Recycling Plant, which also undergoes additional clarifying for certain uses (eThekwini City, n.d.; Ndaba, 2011; Veolia, n.d.-b). Neither of these are involved in value recovery; however, Sasol currently has an innovative project for biogas and associated electricity production, described in Section 2.7.4. Until recently, the focus in the mining industry has been entirely on mitigation of environmentally damaging factors in wastewater; however, there is an increasing body of research into the possibility of value-added products (Harrison, et al., 2014). To date there are no known examples of implementation.

Anecdotally there is an awareness that the agriculture and food processing industries use anaerobic digestion units with biogas collection. At the South African International Renewable Energy Conference held in October 2015, Tiepelt (2015), speaking of biogas from waste, claimed that there are approximately 350 small-scale units, 280 units at WWTW, and 70 units in commercial operation. He did not specify the size cut-off for 'small' units. Notes of information given by speakers at African Utility Week 2016, 17-19 May, Cape Town (Global Utility Week Series, 2016), indicate that this is accurate at order of magnitude level.

It seems that at this point there is no commercial production of value-added products from wastewater in South Africa, other than biogas and water itself. Biogas production remains limited, with even less of the second step of biogas to electricity.

2.7.3 Municipal wastewater

The most often cited example of resource recovery is Johannesburg Water's Northern Treatment Works near Diepsloot where a unit was installed in 2012 that generates electricity from biogas produced in the WWTW. The project involved refurbishing and upgrading existing anaerobic digesters, implementing high-performance mesophilic anaerobic digestion with pre-thickening and cell lysis (Naidoo, 2013). The energy installations are combined heat and power (CHP) with the heat used for heating the anaerobic digestion units and the electricity used in other WWTW operations such as aeration. The improved anaerobic digestion process increases biogas production and quality, achieving the quality required by the power units. The added benefits are reduction in corrosion of equipment and production of a sludge that meets the standards for organic compost (Franks, et al., n.d.; City of Johannesburg, n.d.).

Several significant challenges must be overcome with this installation as noted in a GIZ–SALGA report (Franks, et al., n.d.). The major challenge was performance undercapacity, with sludge production running at about half the expected volume, and average methane content of 62% of that expected. As a result, the CHP units are running well below capacity, with an electricity production of 1600 MWh/year instead of an estimated 5000 MWh/year. This report intimated that the four high-performance anaerobic digestion units would be supplemented with a further two in an attempt to rectify this.

The original reports provide information about roll-out in other City of Johannesburg WWTWs; however, no reports could be found of implementation in other locations except for one listing (Muldersdrift WWTW) in the SABIA project database dated June 2014 (SABIA, 2014).

The SABIA project database for biogas lists numerous 'planned' projects and a number of existing landfill gas projects. Other than the two major Johannesburg projects, the only existing projects in the wastewater space are six listed for the Western Cape (Table 19) that all combine solid waste and sewage. It is likely that this reflects the fact that there was contact with a locally based organisation, GreenCape (see Section 2.7.1), which had collated local information. It is possible that there is a similar number of projects other provinces, but with no local organisation to broker information, these are not recorded in the open sources.

Table 19: Existing wastewater biogas-generating projects listed for the Western Cape (SABIA, 2014)

Province	Local municipality	Technology	Feedstock	Capacity
Western Cape	City of Cape Town – Philippi	Anaerobic digestion	Municipal solid waste (MSW), organics and sewage	15 t
Western Cape	Cape Winelands – Stellenbosch	Anaerobic digestion	MSW, organics and sewage	94 t
Western Cape	City of Cape Town – Noordhoek	Anaerobic digestion	Volatile animal waste and sewage	60 t
Western Cape	Overberg – Stanford	Anaerobic digestion	MSW, organics and sewage	117 t
Western Cape	West Coast – Riebeek Valley	Anaerobic digestion	MSW, organics and sewage	164 t
Western Cape	West Coast – Riebeek Valley	Anaerobic digestion	MSW, organics and sewage	88 t

In 2015, results from scoping studies for biogas potential in nine South African municipalities were reported (Ferry & Giljova, 2015). The summary notes that the potential can be limited by low inflows and by the wastewater treatment process used. Potential can be increased by proximity to another industry suitable for biogas production.

2.7.4 Technology development

Most of the service providers mentioned offer designs involving technologies developed elsewhere, in particular Europe. However, there is one major development project in South Africa relevant to WWBR.

Towards the end of 2013, Sasol launched a pilot plant on its R&D campus in Sasolburg, Free State. The plant uses an anaerobic membrane bioreactor to produce biogas using the effluent from the gas-to-liquids petrochemical plant, with subsequent conversion of the biogas to electricity. This technology was developed through a collaborative effort, including a sponsored UCT Civil Engineering PhD (Van Zyl, 2008), input from the technology of US-based General Electric and the Sasol research team. The pilot plant has a feed rate of 350-1000 ℓ/h (IndustrySA, 2014; Tshwarisano, 2016).

The petrochemicals group announced in April 2015 that the conceptual design for the full-scale commercial process would be available for roll-out by the end of that year. The design is for a 60 Mℓ reactor expected to generate up to 40 MW of electricity. Unfortunately, the first installation is likely to be at Sasol's proposed gas-to-liquid plant in Louisiana, US (Oliveira, 2015; Tshwarisano, 2016), rather than in South Africa.

2.7.5 Service providers

One of the larger companies offering design, equipment, construction and operation within the South African wastewater treatment arena is Veolia. The information they supply mentions decontamination of wastewater, recycling of water, reuse of sludge and recovery of commodities from wastewater (Veolia, n.d.-c). They are one of the few service providers who specifically mention by-products (fertiliser and biogas). They also state, "Veolia is also developing the conversion of wastewater treatment process plants into biorefineries capable of producing energy as well as valuable by-products such as biopolymers" (Veolia, n.d.-c). This was the only reference to biopolymers or biorefineries found in service provider literature.

There are 37 case studies and some newer press releases on their website; however, only the latest one specifically mentions biogas recovery. In 2014, Veolia was awarded the contract to design, construct and operate a wastewater treatment facility for Distell, a spirits, wine and cider producer situated in Stellenbosch, Western Cape (Bizcommunity, 2015; Veolia, 2014; Western Cape Business News, 2015). The Biothane Biobulk® classic continuous stirred tank reactor (CSTR) anaerobic digester will use industrial effluent from the three Distell sites in Stellenbosch as feedstock. The recovered biogas is transferred straight to the boiler producing steam for the distilling process. This plant will be able to treat 1000 m^3/day of effluent with 8.6 t/day COD and was scheduled to come online in March 2016.

Talbot and Talbot have installed a number of anaerobic digestion plants in South Africa, ranging from feedstocks of 1 t COD/day to 25 t COD/day. Applications include those at SAB and Coca-Cola. The biogas may be used to raise steam or in CHP operations.

There are, of course, other service providers in the wastewater arena; however, few mention relevant projects on their websites and little technical information is provided. For example, Project Assignments Consulting Engineers, who install Paques anaerobic digestion systems, mention installation of an anaerobic digestion producing biogas for CHP at a "large poultry abattoir" (Project Assignments, n.d.). A much smaller company, iBert, supplies biogas-electricity installations and mentions an abattoir, a cheese farm and a piggery on their LinkedIn page (iBert, 2015).

No other service providers were found with biogas-electrical projects featured on their websites. In addition, it is apparent from personal communications that there are a small number of wastewater beneficiation studies and installations which have been concluded on behalf of unnamed entities. However, client confidentiality means that the details are unavailable. The capital outlay was identified as a hurdle to project implementation by several of the respondents.

There are multiple companies supplying off-the-shelf anaerobic digestion units of various sizes designed for biogas collection.

2.7.6 Conclusions regarding industrial initiatives

This investigation was challenging as much of the information related to proposed projects and many of the scoping studies and installation projects are client confidential. From the information gathered, it appears that opportunities for valorization of wastewater are still largely unrecognised in South African industry. A number of front runners have installed biogas facilities; however, these are not yet a standard feature. Furthermore, the recovery of energy still requires optimisation in several of the installations. This status suggests immense opportunity for value recovery from South African wastewaters.

2.8 The Wastewater Biorefinery Concept Positioned in South Africa

The concept of the WWBR is new on the global stage and integral to the shift towards a circular economy. Currently, South Africa has not yet embraced the implementation of the "value-from-waste" basis of the WWBR to any significant extent, despite the presence of a significant body of relevant quality research and discrete examples of implementation. This is perceived to result partly from the lack of information on South Africa's wastewater streams and partly from a lack of awareness of the potential for simultaneous value recovery, water treatment and water recovery.

The CDP was set up in 2000 by a consortium of corporations to encourage self-reporting and to enable reduction of carbon footprint globally. The CDP 2015 report states:

> *"There have been some encouraging improvements in the quality of disclosure. Nonetheless, the South African response rate to CDP's water program continues to be low, with just over half the companies responding. This does not reflect the significance of water-related risks in the country, and might suggest that companies are overlooking the severity of these risks.*
>
> *There has been an increase in the number of respondents identifying water-related opportunities, including a particular increase in the number of companies identifying opportunities for enhancing brand value." (CDP, 2015)*

Industry has shown some interest in generating energy from their waste in the form of biogas. This is an established, and therefore lower risk, technology globally. The increasing electricity prices and energy insecurity makes it an increasingly attractive investment.

The lack of available information on wastewater streams and their handling from industry may indicate a fear of litigation for non-compliance of their wastewater for discharge, but it may also indicate lack of a clearly articulated need for beneficiation of the wastes, with a focus on removal of the waste problem only, rather than realisation of value. For example, in food wastes, the waste is often relocated to animal feed. While this presents a low-value market, it fits into the core business and established supply chain and ecosystem of the producers of the waste. These industries seem reluctant to try new technologies that upset established partnerships. This contrasts to complex wastewaters that do not have an existing outlet, for example municipal wastewater and abattoir wastewaters.

The financial implications for industry to commit to WWBR is very important. Key questions to consider include:

- Is a new plant required or can an existing plant or part thereof be retrofitted?
- Is technology being bought in or can internal technology be used?
- Is it cheaper or less risky to pay penalties for not complying with effluent standards than to build a WWBR? What is the integrated financial upside?

Despite increasing awareness of the potential savings that can be achieved by more efficient water use and recycling, the level to which opportunities have been implemented varies widely between organisations (Cohen, et al., 2014). Capital cost of implementation and financial return are cited as the primary reasons for not implementing recycle and recovery systems. All investments are justified on the basis of financial return often regardless of co-benefits for the environment. Water management systems seldom achieve returns comparable to other investment opportunities.

For WWBR to be accepted in the industry context, the value-add has to be significant to offset the greater perceived risk. To use the metaphor of the crude oil refinery, relatively low-value products from wastewater like biogas, fertiliser and animal feed should be considered the equivalent of "heavy vac gas oil" or "asphalt" of biorefineries – the leftovers after the higher value products are refined from the crude stream. Currently, they are considered the only valuable products, which limits the perceived potential of WWBR.

3 CRITICAL CONSIDERATIONS FOR WASTEWATER BIOREFINERIES IN THE SOUTH AFRICAN CONTEXT

In order to assess the suitability of WWBR in South Africa, several critical criteria need to be addressed. This chapter provides an overview of these considerations, with direction for the detail of subsequent chapters in this report. The effects of external factors are discussed in Section 3.1, looking at general economics and government policies. This is followed by three sections surveying the issues that must be accounted for during evaluation: potential wastewater feedstocks (Section 3.2), potential biorefinery products (Section 3.3), and elements of the WWBR process (Section 3.4). Finally (Section 3.5), the dynamics influencing integration of all these aspects into the WWBR are reviewed.

3.1 Economic and Policy Considerations

3.1.1 The effect of economics on the WWBR

The economics of wastewater treatment in South Africa

Van der Berg (2009) studied the South African wastewater market in terms of business opportunities and export promotion for Dutch companies. Promising market segments and a listing of opportunities in South Africa are provided in Table 20. Van der Berg (2009) stated that a major factor within the South African economy obstructing development in wastewater was the lack of investment in infrastructure, particularly power supply and water and wastewater infrastructure, with a resulting decline in water quantity and quality. The main elements of the declining water quality are (raw) sewage effluents, eutrophication and acid mine drainage. The most frequently mentioned causes related to the issue of water quality are the lack of enforcement of laws and regulations, non-allocation of funds and the shortage of skills. The non-compliance of WWTWs presents the most severe problem, with a number of causes and major effects. (Chernick, 2016; Schneider, 2016)

Table 20: Technological opportunities in South African wastewater segments (Van den Berg, 2009)

Segment	Opportunities
Collection and sanitation	Upgrading of wastewater pipeline infrastructure and new sanitation concepts
Industrial	Innovative technologies for rehabilitating industrial wastewater
Domestic wastewater	Wastewater treatment equipment and treatment plants, private sector involvement and upgrade of existing WWTW
Reuse	Membrane technology, domestic water reuse and industrial process water recycling

In terms of water infrastructure, South Africa is currently facing its worst drought in 23 years. This trend is expected to continue due to climate change (Bellprat, et al., 2015). Further, approximately 25% of municipal water is lost through leaks, and 55% of municipalities could not provide accurate water statistics (DWS, 2015a). This report proposes that the gap between water supply and demand in South Africa must be closed by innovative ways to ensure that more wastewater is treated. Further, water should be conserved through better maintenance of the existing infrastructure. Public awareness of the fragility of water security in South Africa should add impetus both to the ability of government to enforce regulations and to the recognition of responsibility in the private sector.

In the intervening years since Van der Berg's (2009) study, the power supply in South Africa has remained unstable, with a combination of intentional rolling blackouts (load shedding) and major increases in the cost of electricity. In June 2015, academics calculated that the electricity price had doubled in real terms since 2009 (Parsons, et al., 2015). Although Eskom is investing in new power plants to increase the supply of electricity, project delivery is problematic (SABC, 2016) and energy availability is still compromised. Also in June 2015, the International Monetary Fund, "singled out delays in easing electricity shortages, and to (sic) policy and regulatory uncertainties, as chief constraints to economic growth" in South Africa (News24, 2015). While this is essentially an inhibitory factor regarding investment, it could also make the production of bioenergy more attractive.

Van der Berg's (2009) analysis of the market potential resulted in a list of market drivers and restraints, concrete business opportunities and an overview of competition in the market. One of the most important market drivers is the increased enforcement by government, which is likely to stimulate spending in this sector in the coming years. Other drivers for this sector are increased feasibility of investments due to increased cost of water and energy, technological developments and the need for improved treatment as a result of increased complexity of wastewaters. In conclusion, Van der Berg (2009) considered the wastewater treatment market in South Africa to be a competitive one, with well-established international competition and many international companies already active in all investigated segments (Section 2.7).

The economics of the WWBR

The WWBR is ultimately a production process and, as such, must be driven by economic considerations. Profitability is the key to the long-term viability of the WWBR and depends on three strands: capital expenditure (capex), operating expenditure (opex) and product value (Bozkurt, et al., 2016). This section presents a qualitative economic analysis of WWBRs with the aim of highlighting critical factors influencing profitability.

Capex is the up-front financial outlay related to the cost of the design process, processing equipment and ancillaries, and construction of the biorefinery. These, in turn, are determined by several factors, including the process design, the size and the location of the system. In a presentation on biorefinery economics dealing with a biomass refinery, Bohlmann (2006) listed pretreatment and product recovery as the main capital-intensive processes. The author recommends the production of co-products, or a diversified product offering to provide economic synergies, and lists wastewater treatment as a remaining technical challenge. The pretreatment in a WWBR will be less intensive than in a lignocellulosic biorefinery, and the wastewater treatment is by definition resolved. The complex, variable and intermittent nature of wastewater streams may impact on the capital cost of producing particular products due to the potential need for specialised systems to handle this variability and deliver consistent product quality.

Opex usually includes the cost of raw materials and energy as the major costs. The WWBR concept offers the opportunity to utilise cheap or free raw materials as the bulk raw materials as opposed to a traditional lignocellulosic biorefinery where the cost is composed of feedstock cost 25-40%, reagents 10-35%, and transport and logistics 5-10% (EuropaBio, 2011). Since most of the microbiological processes considered for the WWBR system use robust naturally occurring mixed microbial cultures, energy requirements for heating are negligible, although cooling may be required. The combination of high volumes and a significant solids component for many wastewaters can result in high costs for pumping. A key factor in operating costs is the cost of DSP. In a large-volume wastewater system, this requires careful attention at the design stage. It is recognised that the low (no) cost of bulk raw materials may be offset by the volume-associated pumping, aeration and DSP costs, and potential constraints to productivity (Kong, et al., 2010; Theobald, 2015). These issues require careful scrutiny.

Apart from the capex and the ongoing cost of production, profitability is influenced by the selling price of the product. Bioproducts are often classified with respect to their price into high-value niche products, intermediate value products and bulk commodity products. High-value products are often produced in small quantities (Grotkjær, 2016). Furthermore, these products usually demand high purity, thus DSP costs are significantly reduced by using simple and consistent feedstocks. Typically, the raw materials form a minor part of the production costs of high-value products. These factors suggest that, typically, high-value products are less suitable for production in WWBRs, or alternatively form co-products. Bulk commodity products are usually demanded in large quantities. Commodity products where purity requirements are also typically less stringent are well suited to WWBRs. In a WWBR, there is the potential to produce lower quantities of intermediate value products upstream of production units for lower value bulk commodity products. A possible negative factor in terms of impact on product economics includes the dilute nature of the raw material, which requires processing of very large volumes of feed streams to achieve the bulk needed for commodity products. It is also important to consider the downstream operations required for product recovery and the positioning of the WWBR relative to the product market. The particular products for the WWBR must be chosen with these multiple factors in mind; however, the benefit of the WWBR approach is the potential to offset waste treatment costs against value derived from products.

In Figure 5, the impact of the various factors on the profitability of the WWBR, directly or by influencing other factors, is considered. Each interaction is labelled and elaborated in the list below the diagram.

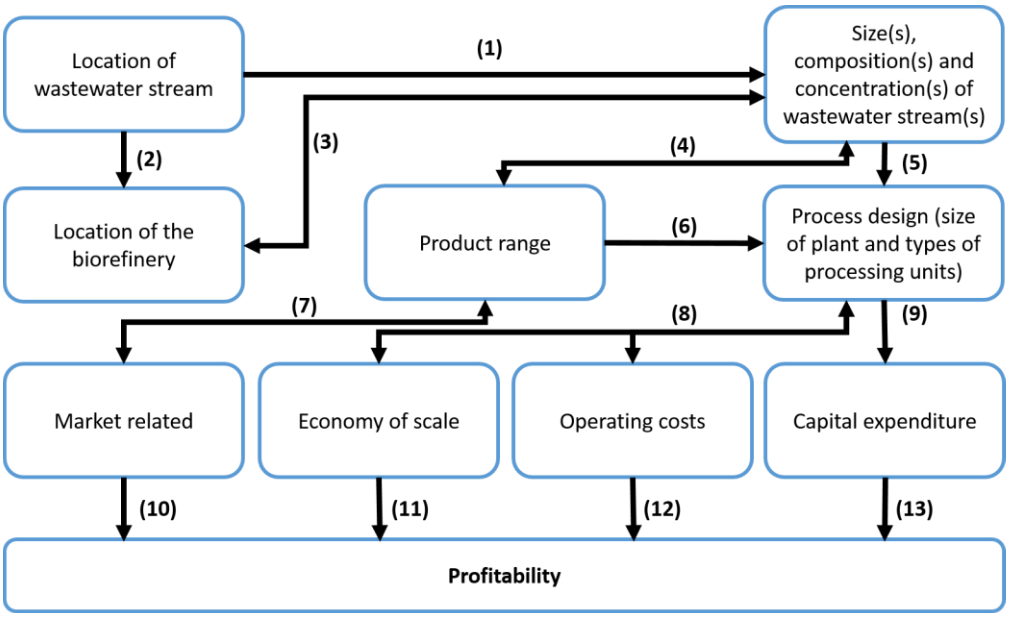


Figure 5: Factors affecting the profitability of the WWBR

(1) The geographical location of the wastewater stream will determine which other wastewater streams can be used based on proximity. This determines the size and properties of the inlet stream to the biorefinery.
(2) The location of the wastewater stream influences the location of the biorefinery to avoid pumping or transportation costs.
(3) The sizes and properties of the wastewater streams available in a certain geographical location influence the location of the biorefinery. The location of the biorefinery impacts access to other wastewater streams.
(4) The sizes and properties of available wastewater streams influence the type of products that can be produced.
(5) The sizes and properties of available wastewater streams, and (6) the product range influence the process design.
(7) The product range influences the markets available for infiltration. The size of the market influences the types of products to prioritise: i.e. some products are more profitable than others.
(8) The size of the operation influences the economy of scale and the operating costs. The types of processing units and control systems also affect the operating expenditure of the process.
(9) The sizes and types of unit operations as well as the complexity of the process influence the capital requirement.
(10) Market size and product acceptance affect the profitability of the biorefinery directly.
(11) Economy of scale influences profitability directly.
(12) Opex influence profitability directly.
(13) Capex influences profitability directly.

The economics of a WWBR may be influenced by the value of the clean water. This is not accounted for above; however, value can arise from the value of reuse (which leads to lower water consumption) or from mitigation of the transgression of standards (Winpenny, et al., 2010). Economic studies may assume offset of wastewater treatment (Fernández–Dacosta, et al., 2015), but in the context of South Africa, or any country with poor enforcement of environmental laws, the scenario against which profitability is measured is one of no treatment rather than one of conventional treatment. The value of the clean water is therefore, at least in part, predicated on governmental policies and regulations with respect to effluent discharge standards as mentioned in Section 3.1.2 and on the geographic location determining the value of reuse.

One of the difficulties in positioning expenditure on a WWBR is the emotive issue of spending money on what is still perceived as waste. This is compounded by the unfortunately still-common perception that the cost of waste treatment is an avoidable expense.

3.1.2 The effect of wastewater policy on the WWBR

Standards for treated effluent

To establish a good understanding of water effluent criteria, the wastewater treatment standards of South Africa must be considered. The standards listed in Table 21 were introduced by the Green Drop certification in 2008. They are updated annually as part of the incentive-based regulatory model. The Green Drop certification measures the performance of WWTWs and sets a target of 80% compliance with wastewater effluent standards. The 2013 Green Drop Report indicated that 41% of the 914 water supply systems assessed require attention. Similarly, 55% (or 821) of WWTWs require serious, critical and urgent refurbishment (DWS, 2015a). The model includes strengthening the regulatory approach while refocusing the Local Government Support Model to improve the problem-solving capacity and move towards preventative maintenance instead of crisis-management (WISA, 2009).

Table 21: General authorisation standards for treated effluent (DWA, 2013)

Substance/Parameter	General Limit	Special Limit
COD (mg/ℓ)	75*	30*
Electrical conductivity (mS/m)	Intake +70; Max 150	Receiving +50; Max 100
Faecal coliforms (per 100 mℓ)	1000	0
pH	5.5-9.5	5.5-7.5
Ammonia (ionised and un-ionised) as nitrogen (mg/ℓ)	6	2
Chlorine as free chlorine (mg/ℓ)	0.25	0
Fluoride (mg/ℓ)	1	1
Nitrate/nitrite as nitrogen (mg/ℓ)	15	1.5
Orthophosphate as phosphorus (mg/ℓ)	10	1 (median); 1.5 (max)
Soap, oil or grease (mg/ℓ)	2.5	0
Suspended solids (mg/ℓ)	25	10
Dissolved arsenic (mg/ℓ)	0.02	0.01
Dissolved cadmium (mg/ℓ)	0.005	0.001
Dissolved chromium (VI) (mg/ℓ)	0.05	0.02
Dissolved copper (mg/ℓ)	0.01	0.002
Dissolved cyanide (mg/ℓ)	0.02	0.01
Dissolved iron (mg/ℓ)	0.3	0.3
Dissolved lead (mg/ℓ)	0.01	0.006
Dissolved manganese (mg/ℓ)	0.1	0.1
Mercury and its compounds (mg/ℓ)	0.005	0.001
Dissolved selenium (mg/ℓ)	0.02	0.02
Dissolved zinc (mg/ℓ)	0.1	0.04
Boron (mg/ℓ)	0.1	0.5

The Green Drop Report also highlights that optimising WWTWs, for example, through energy recovery or energy efficient design (Ferry & Giljova, 2015) has the potential of reducing operational costs or even make the treatment facility financially self-sustainable. This possibility could serve as an incentive for municipalities to consider upgrading their plants while including new technologies for cost recovery (WISA, 2009). One risk of generating economic value from wastewater is that there may be a trade-off between meeting the requisite water quality and maximising economic return. Thus, the compliance of the effluent can become a secondary concern after profit. Verster, et al. (2013) recommended that the production of value should be housed within a separate unit operation to the polishing of final water quality to prevent unnecessary compromise of water quality standards. After extracting products, the cleaned water must still adhere to legislated standards. The WWBR can be incorporated into existing WWTW or operated on the premises of the generator of an industrial wastewater. Some of the challenges are mitigated by contracting plants to private companies through a variety of public private-partnership (PPP) or build-operate-transfer (BOT) models (see Section 3.1.3); however, clear cooperation with regulatory requirements is requisite.

Broader policy considerations

In 2015, the WRC published "South Africa's water research, development, and innovation (RDI) roadmap: 2015-2025" in collaboration with the DST and the Department of Water and Sanitation (DWS). The RDI Roadmap (WRC, 2015d) provides a structured framework to focus the contributions of RDI activity in the implementation of national policy, strategy and planning in water resource management in South Africa. There are four key objectives:

- Increase the availability of water.
- Improve the governance, planning and management of supply and delivery.
- Enable water and sanitation services to operate as a sustainable "business".
- Increase the efficiency and productivity of water use.

The water community as a whole was divided into four sectors, namely, agriculture, industry, public sector and environmental protection. Interventions in each sector were identified to provide lists of recommended actions that would satisfy each need. The needs and interventions were categorised into seven clusters. A ten-year programme of action and investment was created for each cluster. The seven clusters are:

Water supply

1.1 Increase ability to make use of more sources of water, including alternatives.
1.2 Improve governance, planning and management of supply and delivery.
1.3 Improve adequacy and performance of supply infrastructure.
1.4 Run water as a financially sustainable "business" by improving operational performance.

Water demand

1.5 Improve governance, planning, and management of demand and use.
1.6 Reduce losses and increase efficiency of productive use.
1.7 Improve performance of pricing, monitoring, billing, metering and collection.

The report highlighted various needs (Table 22). The interventions needed in the agriculture, industry, public, and environmental protection sectors are shown in Table 22.

Table 22: Clustered needs identified by the four sectors, and their summarised interventions (relevant excerpts from Table 19 from WRC Water RDI Roadmap (2015d))

Needs	Agriculture	Industry	Public	Environment
Increase use of treated effluent	• Implement efficient treatment management system. • Address public perception issue. • Catalyse linkages between those that discharge, producers and users – e.g. mines and farms.	• Improve regulatory frameworks. • Improve the quality of decision-making information.	• Improve regulatory frameworks. • Improve the quality of decision-making information. • Implement efficient treatment management system. • Address public perception issue.	• Investigate treated effluent to artificial recharge of groundwater as potential conjunctive source. • Increase ability to optimise mix for context.
Increase use of wastewater	• Fitness for use.	• Integrate better with agriculture and energy production.	• Improve regulatory frameworks to improve the quality of decision-making information. • Implement efficient treatment management system. • Address public perception issues.	• Improve performance and cost of purification.

Needs	Agriculture	Industry	Public	Environment
Optimise ability to manage water resources from source to source in an integrated way	• Optimise ability to manage water resources from source to source in an integrated way.			• Refine accountability along the value chain. • Implement current legislation water research node. • National Water Act, and National Water Resource Strategy, South Africa (NWRS).
Improve financial sustainability of the water system			• Ring fence — "run water as a business in municipality".	
Improve operational efficiencies			• Ring fence — "run water as a business in municipality".	
Improve cooperative governance with respect to planning and management cross-sectoral	• Enable water ordering. • Improve management of distribution.	• Systematically increase water independence. • Map footprint. • Develop reduction strategy.	• Align with NWRS2 in terms of policy instruments and regulations governing licence applications granted or denied.	
Optimise conjunctive use of water	• Balance use of all sources in an integrated manner.	• Balance use of all sources in an integrated manner. • Minimise demand on supplier (municipality).	• Increase the degree of alignment of the quality of water with use.	
Reduce volume of water use	• Use water-saving crops and varieties.	• Minimise water use, application and losses in primary processes. • Avoid use of water (e.g. optimised or new no water processes). • Recover and recycle condensate. • Reduce steam leakage. • Manage water pressure.	• Stimulate growth more economically (use of water). • Highlight the importance of water and its scarcity to encourage consumers to reduce demand. • Improve dry solution systems and encourage acceptance.	
Improve efficiency of water use	• Encourage uptake of land and water use practices. • Introduce irrigation systems and improve performance. • Optimise fertiliser use. • Increase effectiveness of knowledge transfer. • Increase levels of rehabilitation.	• Reduce water in ancillary processes. • Reduce demand for domestic water.		
Increase levels of water reuse	• Reduce volume of wastewater, recover and recycle	• Reduce volume of wastewater. • Increase levels of recovery and recycling.		
Minimise output to unrecoverable sources	• Reduce wastewater released to sewers.	• Reduce volume of wastewater released to sewers. • Recycle water streams for water and wastewater treatment.		
Reduce volume and toxicity of pollution	• Reduce rainwater runoff.	• Minimise production of waste (e.g. cleaner production methods).	• Increase WWTWs with Green Drop certification to >95%.	• Maximise natural water resource function (aquatic response).
Minimise discharge of poor quality water		• Minimise production of effluent (e.g. cleaner production methods).	• Increase WWTWs with Green Drop certification to >95%.	

Many of the interventions described in Table 22 can be addressed by applying the WWBR concept to the sector in question. The philosophy of the WWBR includes:

- Producing “zero waste” by valorizing all elements of a “waste”-water stream.
- Maximising reuse and recycling of water through adequate extraction of contaminants.
- Producing energy from residual organic elements in the “waste”-water stream.
- Economically and advantageously treating “waste” water through valorization.
- Integrating neighbouring industries in terms of “waste” water valorization and reuse.
- Complying 100% regarding water released to environment.

In fact, integration of the WWBR is probably the only way of achieving the overall technological remediation envisaged in the report.

3.1.3 The effect of innovative partnership models on the WWBR

The South African water infrastructure is subject to aging effects associated with internal and external stresses, while inadequate maintenance and lack of capital renewal have resulted in further deterioration (Zhuwakinyu, 2012). The DWS is struggling with serious capacity and funding problems; it is estimated that an investment of R1.4 billion is required each year merely to maintain the current infrastructure. The DWS is also faced with a shortage of skilled personnel to implement and supervise maintenance. The problems are further compounded by fading institutional memory as individuals retire, are retrenched or join the private sector (Water, 2012).

In 2014, the minister of the Department of Water Affairs (DWA) said that DWA needed an estimated R670 billion capital investment and infrastructure. Since only 45% of this was funded by the governmental budget, controversial options such as PPPs are being considered (Kings, 2014). Senior department personnel have frequently mentioned that PPPs are the only way to bridge the funding gap. This is opposed by groups such as the Coalition Against Water Privatisation (CAWP, 2003) who maintain that privatisation policies in the 1990s led to a “dramatic increase in the price of water for the poor across South Africa”. However, many municipalities have faced the collapse of their water and sewerage works because of a lack of funding. Impact of inadequate water treatment on the health of communities has been suggested.

There is evidence that at least some of the PPPs result in improved coverage and improved consistency in effluent control (Donnelly, 2015; DWS, 2015b). An example of this model related to WWBRs is the Johannesburg Northern Works bioenergy project (Section 2.7.3) owned by Johannesburg Water. This was built by WEC Projects who still operate and maintain the energy plant (Franks, et al., n.d.). A similar arrangement is becoming increasingly common in industry. A specialist company is awarded the contract to design a WWTW, build it and own-and-operate it for an agreed period. This model addresses the fact that the commissioning entity does not have to envisage expanding into an unfamiliar field or “non-core” business. Further advantages include guaranteed price and availability for any products used in-house and a set fee for water treatment. An example of a BOT is the agreement between Distell and Veolia for a plant producing biogas and reusable water. Situated in Stellenbosch, Western Cape, the facility was due to be commissioned in March 2016 and will be operated by Veolia for ten years (Bizcommunity, 2015; Western Cape Business News, 2015).

3.2 Evaluating Wastewater Feedstocks

Based on a clear need for intensified water reuse, increasing need for alternative sources to supplement electricity supply and a shortfall of funding in the wastewater treatment arena, there is a major incentive for a new approach to wastewater in South Africa. The approach outlined here sets out to realise the opportunity presented by wastewater as a feedstock for bioproducts and energy generated through robust bioprocesses. This potential is holistically encompassed by the WWBR concept. To assess its potential, the wastewater streams available as feedstock are evaluated.

3.2.1 Detailing wastewater streams in South Africa

Stafford et al. (2013) and Burton et al. (2009) report on a study exploring technologies for recovering energy from wastewaters in South Africa. Energy generation through the production of biomass, combustion and gasification, generation of biogas, production of bioethanol, heat recovery and use of microbial fuel cells was considered. A first-order desktop analysis of South African wastewaters was used. Using data collected in 2007 it was found that there was potential for recovering between 3200 MWh and 9000 MWh of energy. This amounts to approximately 7% of South Africa's current electric power supply. Formal and informal animal husbandry, fruit and beverage industries, and domestic blackwater were identified as wastewaters with the greatest potential for energy recovery. Of the technologies reviewed, anaerobic digestion applied to the widest range of feedstocks. Nett energy generated, reduction in pollution, and water reclamation were identified as the main benefits, with emission reduction, fertiliser production and secondary products as additional benefits.

Cloete, et al. (2010) surveyed the water use and effluent production of South African industrial, mining and electricity generation sector. The report stressed the incomplete data on effluent production that highlights a problem faced in South Africa in terms of understanding the exact load of waste that is associated with industry. This is a great concern when it comes to managing the impact of effluent production on the environment.

The WRC has commissioned a series of reports attempting to detail the state of water and wastewater management in various industries. There are 15 reports in the series known as the national surveys or NatSurv documents (WRC, 2015b). These reports are currently being updated, with some of the new reports due to be published in 2016.

The WWBR emphasises recovery and reuse of all elements of wastewater, especially the carbon, nitrogen and phosphorus nutrients, with energy formation being a secondary product. For WWBR purposes, the complete composition of the waste stream is desirable, including variability and complexity. This is more than typically reported. Logistical information is also important, including the volumes available, the distribution and the localities.

3.2.2 *Categorising wastewater streams for WWBRs*

Wastewaters need to be well-categorised to design the appropriate facilities. The approach taken here is to categorise wastewaters according to three factors; namely, volume, concentration, and complexity. Many of these wastewaters, particularly municipal wastewater, have huge flows, in the order of 50 Mℓ/day (CoCT, 2010). These can be quite dilute, with the most common components in the order of milligrams per litre. In addition, wastewaters often exhibit a high level of complexity in terms of the number of components and the variability of components and concentrations. The different groupings of wastewaters each have their specific challenges and opportunities, which this project seeks to define and explore.

Volume

The volume classification must be considered from both an individual plant perspective and in terms of national production. Many wastewater sources, like abattoirs (Section 4.3.3) or municipal wastewater (Section 4.2), have relatively few large industrialised plants with large wastewater flows, with many small plants whose wastewater may be poorly managed, or not treated at all. While smaller plants have greater WWBR potential, at least while the concept is still in infancy because of greater flexibility of operation and smaller volumes, which may translate to lower overall risk, smaller plants often are not regulated effectively. Further, the operations producing the wastewater may not have the funds necessary to invest in adequate waste treatment. Smaller plants may also require cooperation to create the necessary logistics to overcome the limitation of their small size and often scattered or inaccessible locations.

The wastewater treatment plants typically found can be classified as follows according to capacity (DWA, 2009; Van den Berg, 2009):

Type of plant	*Capacity*
Micro	<0.5 Mℓ/day
Small	0.5-2 Mℓ/day
Medium	2-10 Mℓ/day
Large	10-25 Mℓ/day
Macro	>25 Mℓ/day

Figure 7 considers the national potential for using wastewater as raw material, hence is focused on an indication of the total volume of wastewater produced per industry. The size and state of the wastewater treatment plants, or volumes of wastewater generated per site is relevant for considerations of economies of scale. This distribution is considered in Section 4.2.

Concentration

The concentration of dissolved solutes in the wastewater influences their beneficiation potential for products other than clean water. For the purpose of this report, high concentrations are above 10 g/ℓ COD, namely, microbial bioconversions (including growth) can be supported without retained biomass (Nicolella, et al., 2000). Municipal wastewater, for the most part, uses water to transport waste. This necessarily dilutes the components, with a typical value of less than 1 g/ℓ-COD (Henze, et al., 2008), which is recognised as low concentration. Medium concentration lies between these two values. All wastewaters are likely to have varying concentration over time.

Figure 7 considers the potential for using different wastewaters as feedstock. COD values are the most commonly available, hence this metric has been used to compare concentrations. It is noted that this is a limitation for COD-poor nutrient-rich waters. In as far as possible, values for all nutrients are reported in Section 4.3 and other relevant components are noted.

Complexity

Potentially, the most problematic characteristic of wastewater is the level of complexity. Some waters, like municipal wastewater, tend to be highly variable while changing concentration and, in some instances, composition continuously. These waters are considered by municipal managers as 'receptacles', meaning that the compounds that make their way into the water are not controlled or predictable (Coetzee, 2012).

The complexity can be considered according to the predicted difficulty of treating the wastewater. This relates primarily to the number of different components present, but also to the presence of components that may require more treatment steps, or may interact with each other to prevent treatment, be it through chemical interaction or through physical interaction. Physical interactions may range from the micro level, like foaming in the case of fats and oils, to the macro level, like the clogging potential of non-dissolved components like feathers or earbuds that may complicate treatment or increase maintenance costs.

The complexity of wastewater is classified according to the authors as:

Low	Composition does not change much, <5 main components
Medium	Composition changes in predictable manner, 5-15 main components
High	Composition changes often and unpredictably, >15 main components

Figure 7 rates the different categories of wastewater using this categorisation to indicate the anticipated difficulty of designing a WWBR which is able to deal with the components present.

3.2.3 A matrix representing wastewaters as feedstock

Figure 6 introduces a matrix for qualitative representation of feedstock qualities according to the variables suggested for categorisation in Section 3.2.2: volume, concentration and complexity.

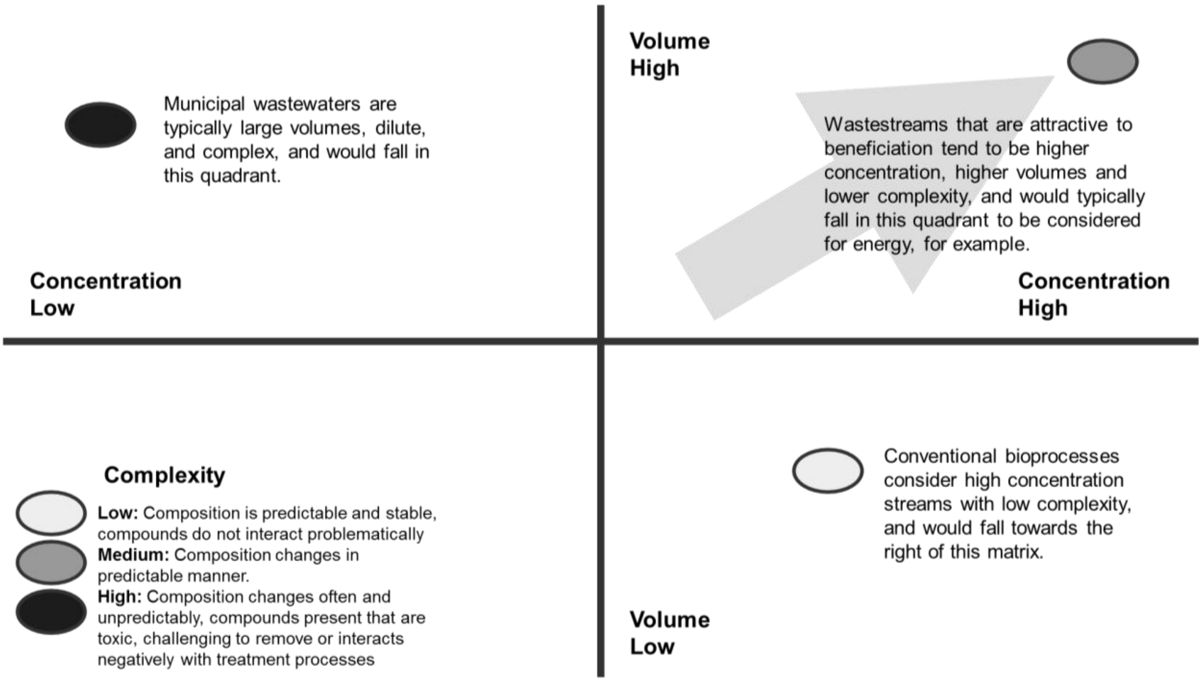


Figure 6: Matrix for qualitative representation of feedstock qualities of volume, concentration and complexity

This matrix is used in Figure 7 for an initial subjective comparative categorisation of a broad spectrum of wastewaters in South Africa. For example:

Brewery wastewater is an example of low complexity. The wastewater is well characterised because the preceding process is well understood and controlled from a biological perspective. The components do not interact negatively with each other, and can be treated by few unit processes.

The textile industry is an example of medium complexity. The dye processes change between batches, and the presence of high salt and often of heavy metals complicates treatment. Both physico-chemical and biological treatments are required. The wastewaters are generally produced in a predictable manner; hence, an established treatment chain can be applied to different sites with similar results.

While abattoirs have high concentration wastewaters, they contain complex biological molecules like blood and fats, while also having physical components like feathers and skin. While the wastewater produced by large, well-managed abattoirs may be more predictable, smaller plants may combine several waste streams or use wastes for secondary products, which introduces additional complexity.

Municipal wastewaters are mostly dilute. They contain a large variety of components, some of which may fall below detection limits. Backyard activities and industrial discharge changes the character of the wastewater across sites and associated treatment required and product potential. Further intermittent disposal aggravates variability.

Chapter 4 contains a quantitative presentation of data collected on different wastewater streams from various industries in South Africa. The later sections in Chapter 4 attempt a more in-depth analysis of the wastewaters in terms of the potential value and possible complications involved in using the wastewater from each industry as feedstock for WWBRs.

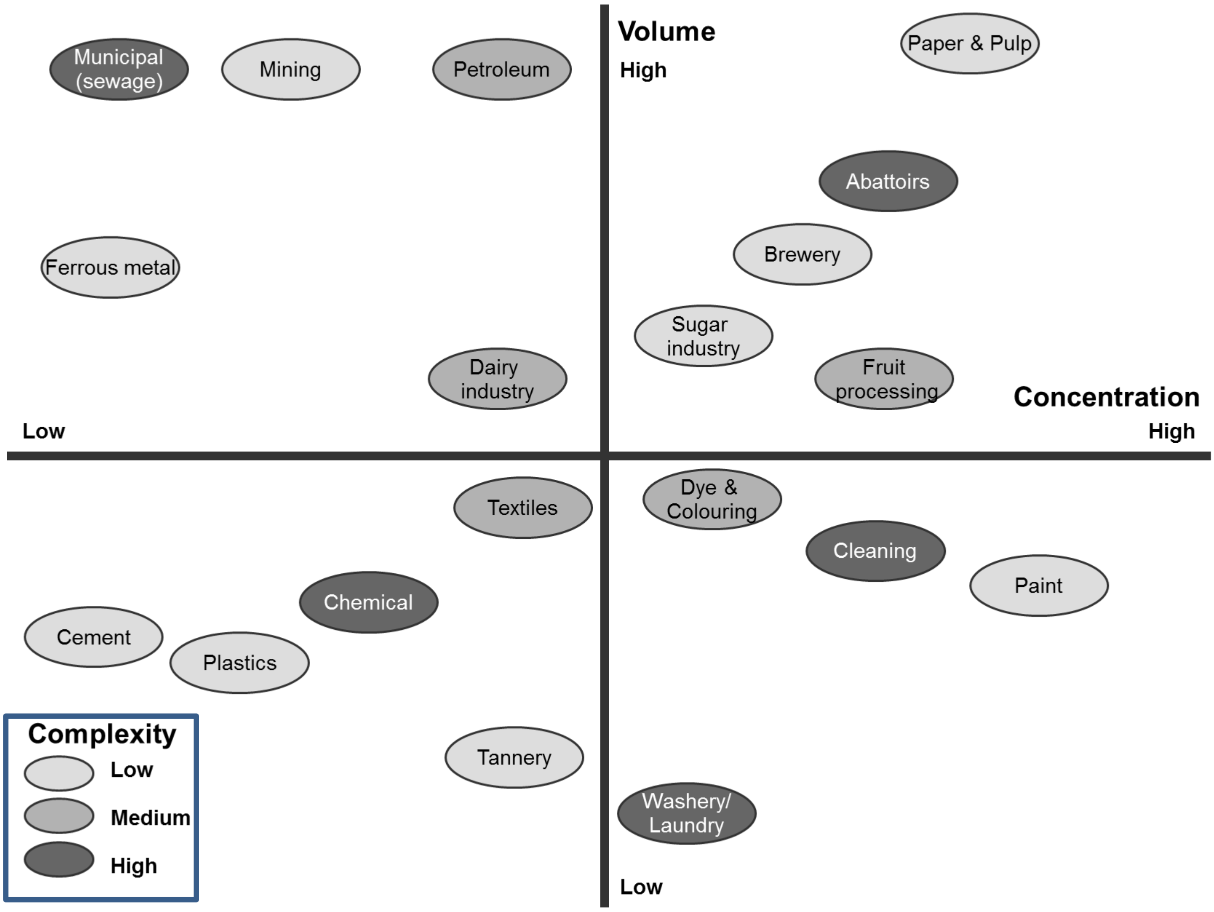


Figure 7: Matrix illustrating grouping of wastewater in terms of volume, concentration and complexity

3.3 Evaluating Biorefinery Products

Not only technical considerations are important when evaluating products for the WWBR. Aspects of the economics (Section 3.1.1) of the biorefinery are an integral part of decision-making. In addition to the typical economic factors of operating cost vs potential income, additional considerations include potential for niche products, which require careful market research. Further diversification of products can be economically stressful for the entity producing the wastewater. Policy plays a vital role here too. Firstly, there is the possible necessity for unprofitable products retained for the sake of producing compliant final effluent. Secondly, there are limitations regarding standards required for some products, especially anything associated with human consumption.

3.3.1 Categorising potential products

A wide range of possible products can be formed across the various units of the WWBR. For the purposes of this project, the range products are categorised as follows:

- First level products: bioproducts derived from microbial bioreactors.
- Second level products: biofuels and bioenergy.
- Third level products: processed biomass (fertiliser, animal feed, fibre, compost).
- Fourth level products: Acceptable quality water: fit-for-use, or compliant for discharge.

First level products: bioproducts

Bioproducts can further be classified into two categories. The first is those produced by breaking down complex molecules into basic building blocks that can then be used for chemical synthesis. Potential bioproducts in this first category include organic acids, industrial enzymes, VFAs, pigments and alginate (Pandey, et al., 2010). The practical approach for the production of metabolites and enzymes can be related to different areas (paper deinking, paper recycling, agricultural residue utilisation, pesticide biodegradation, fodders, olive and seed oil residues, pruning, fuels, paper pulp production, etc.) and each of them require a different set of biotechnological conditions (Pandey, et al., 2010).

The second category includes function-based products that use complex macromolecules with minimal modification and purification. Examples of these are bioflocculants, biosurfactants or soil conditioners.

Thus, the influent wastewater can be classified in terms of potential products:

- Very complex, diffuse wastewater from which niche products can be produced, not related to the producers of the waste (e.g. domestic municipal wastewater).
- Defined wastewater, but most feasible products fall outside of the market focus of the industry player producing the water (e.g. brewery waste).
- Defined wastewater, with potential for conversion into a product used within the process or market focus of the industrial player.

Second level products: bioenergy and biofuels

Since considerable amounts of energy are needed in a WWTW to aerate the aerobic processes and to pump or transport the large volumes of water and biomass from one unit to the next, the GHG contribution to supply clean water is becoming environmentally unsustainable (Sheik, et al., 2014). Hence, energy is a key factor in the WWBR and these "second level" products are important as they are from almost any biologically based process, particularly one based on waste materials and typically form a key unit operation of the WWBR.

Potential bioenergy products include biogas, algal lipids for biodiesel and biomass for combustion, gasification or pyrolysis. Liquid alcoholic biofuels are only of interest for concentrated product streams. However, since bioenergy production is relatively common as a wastewater treatment strategy and thus well characterised (Bharathiraja, et al., 2014), this project does not investigate the conversion processes for this category in detail. These products are, however, considered in the process flowsheet analysis.

Third level products: processed biomass

In order to fulfil the "zero waste" and "zero harm" potential of the WWBR (Sections 2.2.1 and 2.3), the process needs to go beyond these two levels especially in the arena of the macrophyte and fungal processes. These two processes typically produce products such as fibre, hyphae, compost, and agricultural products, as well possible biomass-for-energy and bioproducts. Sludges for fertiliser and associated operations may also be handled in this category. Third level products are largely low-value and non-specialised bulk products, but nevertheless specific to the particulars of the process concerned. More research is needed in this area, since these products have not been addressed in traditional industrial bioprocesses whereas the WWBR concept necessitates them. This project does not explore the production of this level of product in detail, but does consider it in the process flowsheet analysis.

Fourth level product: Water as a product

Water is a key product of the WWBR with its final use defining its required properties. This could be "fit for purpose" for recycling back to the industry from where it originates, "fit for purpose" for an alternative use, geographically aligned e.g. irrigation water or cooling water, as potable water, or for release into the environment.

3.3.2 Constraints of the WWBR on potential products

The WWBR is established to maximise productivity by ensuring that not only is the wastewater treated to the necessary standard (yielding the outgoing water product), but also that components removed from this wastewater are converted to the selected products that have value economically, socially or environmentally.

Because of the particular challenges of using wastewater as feed, WWBRs are not suitable for all bioproducts. Due to the (generally) dilute nature of the wastewaters, highly energy intensive production processes are not appropriate. It is also beneficial to select culture conditions and products to contribute a selective advantage to the microbial community of interest (Mooij, et al., 2015; Winpenny, et al., 2010). WWBRs, therefore, are most suitable for products that fulfil a defined role in the microbial ecology allowing natural selection for the microorganism of choice (Verster, et al., 2013). Further, the desired product needs to be easily recoverable from the stream – either produced in a different phase, or be recoverable through a cost-efficient process (Verster, et al., 2013).

Products that play a role in the functioning of the treatment works or in the industry producing the wastewater may be favoured. The production of materials required for plant operation from its own waste resources secures a stable market or use for the product and provides additional motivation for introduction to the concept of the WWBR. Moreover, this mitigates the need to expand the core business of the entity in question (Desrochers, 2001).

The regulations and the required level of purity depend on the product. Further, this is impacted by whether the product is for final use or is an intermediate feedstock to a subsequent process (Chen & Zhang, 2015; Ghatak, 2011). Generally speaking, the higher the required purity of a product, the higher the cost of DSP. The required DSP has a major influence on the appropriateness of product selection, as discussed in Section 3.4.5. In addition, the wastewater environment forms a health barrier, actual or imagined, to the direct use of products for human consumption or applications (Dolnicar, et al., 2011; Asano & Cotruvo, 2011).

These considerations will inform the selection of products to impact the economic feasibility of WWBR in South Africa.

3.3.3 Range of potential products for the WWBR

A wide range of potential products and product functionalities can be considered for the WWBR. Their market potential is influenced by the source of the feedstock, with particular potential to supply the upstream process with necessary reagents or to supply products into regionally aligned industries. Routes for product recovery and purity requirements are central to the product selection.

Bioproducts

A selection of the wide range of high-level bioproducts that could potentially be produced from dilute wastewater streams, along with appropriate wastewater resources, is listed in Table 23, based on the review of Fava et al. (2012). It is noted that, in addition to these “Level 1” bioproducts, bioenergy products, fibre products, fertiliser and soil enhancer products, and water as a product are expected to arise from each feedstock.

Table 23: Overview of types of waste streams, their properties and potential "level 1" bioproducts (adapted from (Fava et al., 2012))

Type of waste streams	Properties	Potential products
Vegetable and fruit processing by-products, waste and effluents Hydrolysate obtained from by-products/waste pretreatment of vegetable/fruit waste	High in proteins, sugars and lipids along with particular aliphatic and aromatic compounds	Fine chemicals: -Natural antioxidants -Antimicrobial agents -Vitamins -Bacterial exopolysaccharide (e.g. xanthan gum) Macromolecules: -Cellulose -Starch -Lipids -Protein -Fibres -Plant enzymes -Pigments -Pharmaceuticals -Flavours -Vitamins -Organic acids -Biopolymers -Lubricants -Microbial enzymes
-Sugarcane and beet molasses -Dairy industry (cheese whey effluents) -Vegetable and fruit waste -Effluents of palm oil mill, olive oil mill, paper mill, pull mill -Hydrolysates of starch (corn, tapioca etc.) -Lignocellulosic waste (cellulose and hemicellulose)	High organic content	Microbial polymers (PHAs)
Starch processing wastewater	High concentrations of readily biodegradable non-toxic organic compounds with relevant amounts of nitrogen and phosphorus	-Valorized through the recovery of starch and oligosaccharides -Biotechnological production of bio-pesticides, surfactants and amylases -Single-cell protein production from amylolytic microorganisms and non-amylolytic yeasts
Wastewater with surface contamination problems	High biological oxygen demand (BOD) concentrations	-Organic acids (lactic acid and butyric acid) -Alcohols (ethanol and butanol)
Woody (lignocellulosic) waste		-Furfural (from agricultural residues of sugarcane, corn and wheat) -Lignin (from paper pulp production)
Municipal solid waste		-Intermediary chemicals -Proteins -Enzymes

Products such as PHA are produced from monocultures such as *Cupriavidus necator* (previously known as *Ralstonia eutropha* and *Alcaligenes eutrophus*) (Lopar, et al., 2014). Single-cell protein bacteria include *Cellulomonas*, *Alcaligenes*, and cyanobacteria such as *Spiruli.* Algae such as *Chlorella* and *Scenedesmus* can produce lipids that can be used for biofuels and a range of other products. Moulds (*Trichoderma*, *Fusarium*, *Rhizopus*) and yeast (*Candida* and *Saccharomyces*) may find application in production of organic acids, solvents and furfural (Nasseri, et al., 2011). Biosurfactants are produced from a range of microorganisms such as *Bacillus* sp., *Pseudomonas* sp., *Candida* sp. (Youssef, et al., 2004); the latter two require careful assessment as some members of these genera are pathogenic. Potential bioproducts from fungal action on biosolids include industrial enzymes and organic acids (Chen, 2013; Pandey, et al., 2010).

Biofuels and Bioenergy

The production of methane from organic material by anaerobic digestion is well characterised (see Section 2.7.2 and Section 2.7.3 for examples in South Africa). The technology is widespread and well utilised (Mata-Alvarez, et al., 2000). In this process, an organic carbon source is converted under anaerobic conditions by a mixed consortium of microorganisms via VFAs and hydrogen into methane and carbon dioxide. This gas product can be used as an energy source. This technology has been applied to a wide range of organic carbon sources, usually waste streams, such as vinasse (Moraes, et al., 2015) sewage (Seghezzo, et al., 1998), slaughterhouse effluent (Salminen & Rintala, 2002), manure (Nasir, et al., 2012), food waste, beverage wastewaters, waste from the petrochemical industry and a host of other sources.

In addition to methane production from wastes, another possible energy product is hydrogen, produced either through dark fermentation similar to methane-producing anaerobic digestion, or through photofermentation (Hallenbeck & Benemann, 2004). Production of biohydrogen is a much less mature technology than production of biomethane, and has not been as widely applied. However, it does have potential to be an important source of hydrogen for hydrogen-based technologies such as fuel cells (Levin, et al., 2004).

A currently well-utilised biologically based energy carrier is bioethanol. This can be produced fermenting organic compounds (mainly sugars) to ethanol using yeasts (Gray, et al., 2006). While this technology is used on a large scale throughout the world, it is generally not used in wastewater treatment. It is rather based on more conventionally derived organics, such as sugars from sugarcane or maize, or concentrated water streams from agricultural industries, such as molasses. While there is potential for carbohydrate-rich wastewaters to be used in bioethanol production (Hamelinck, et al., 2005), this is not well suited to dilute waste streams owing to the energy requirements and costs of ethanol recovery.

The use of biodiesel is widespread and often legislated, particularly in Europe. The majority of biodiesel is produced from oil-bearing plant crops (Ma & Hanna, 1999), or waste oil. In the WWBR, an oil-producing microorganism could be used to convert waste materials into lipids for conversion into biodiesel. Examples include microalgae (Schenk, et al., 2008) and bacteria (Li, et al., 2008).

Moving into the wastewater space

Many of the potential products have not been demonstrated in the wastewater space. With the WWBR concept still in its infancy, specific research is needed for most of these, particularly studies well integrated with the proposed feedstock. This is necessary for “Level 1” products, for “Level 2” energy products linked to wastewater feedstocks, but most of all for “Level 3” products associated with the solids and macrophyte bioreactors.

Considering the wide range of products at all levels possible even within the WWBR constraints, selection of products becomes a function of the particular feedstock stream and potential market. This project provides an example of the selection process in the case of first level bioproducts for the bacterial reactor in Chapter 5. Furthermore, it considers the integration of multiple products through the flowsheets presented in Chapter 7.

3.4 Unit Operations and Biological Systems for Bioconversion Needs

In this section, the bacterial, algal, macrophyte and fungal reactors as suggested in Figure 2 are discussed. Separation units needed for DSP in a WWBR are considered. In observations regarding design of units, the unique challenges of the WWBR must be kept in focus, including economic matters (Section 3.1.1) and policy considerations (Section 3.1.2). The general groundwork for technology selection must be laid, considering the opportunities and challenges presented by available feedstocks (Section 3.2) together with a realistic assessment of product options (Section 3.3).

3.4.1 *Bacterial bioreactor*

In traditional WWTW, a bioreactor cultivating bacteria, yeast or submerged culture fungi is mainly used when there are complex streams with high COD entering the process, or with limited land availability. Since bioreactors for bacteria and unicellular yeast have the most compact footprint and can be operated in the most effective configuration, they are attractive. For simplicity, these will be referred to as "bacterial bioreactors" in this report. Typically, a single product bacterial bioreactor also requires skilled operators and may therefore not be suitable for low-maintenance sites.

The critical factors for bacterial bioreactors processing dilute feed streams in the WWTW are biomass retention or the recycling of biomass to achieve higher effective biomass concentration. Recycle of biomass after product recovery may not be feasible depending on the product produced. Further, recycle of biomass demands its flocculation and ready settling as high energy separators are not practical.

Numerous well-characterised reactor conformations function with bacterial catalysts, with "off-the-shelf" systems available. For the particular needs of the WWBR, these reactors must be assessed and the most suitable chosen for further evaluation. This process is captured in Chapter 6 and the start of the necessary follow-up experimental evaluation is presented in Appendix E. There may be key modifications needed in order to tailor the design to microbial selection and concomitant product production.

The bacterial bioreactor can produce a high-level value-added product. The bacterial reactor optimised for productivity does not result in depletion of all nutrients. This reactor may provide high-quality carbon substrate in the form of a predigested feed rich in VFAs as well as residual combined nitrogen and phosphates for use in an algal reactor. Alternatively, the VFA component may be depleted with concomitant energy production in, for example, an anaerobic digester with the carbon-depleted, nitrogen- and phosphorous-containing stream proceeding to an autotrophic algal reactor.

3.4.2 *Algal bioreactor*

While all algae can grow photoautotrophically, a number of species are mixotrophic, being able to grow on organic carbon or CO_2. These algal cultures may grow more rapidly under heterotrophic or mixotrophic conditions than under autotrophic conditions by a factor of 3 to 4 (Kim, et al., 2013). However, the potential for contamination also increases under richer nutrient conditions. These mixotrophic algal systems may be useful to scavenge residual organic carbon while simultaneously carrying out nitrogen and phosphorous removal. Algal growth rate and rate of nitrogen and phosphorous depletion influence the opex in the context of wastewater treatment (Kim, et al., 2013). If the algae need to be selected for a dominant (group of) species, factors like the nitrogen and/or phosphate content need to be controlled. To reduce bacterial contamination, the carbon content of the feed stream to the algal bioreactor can be limited by optimising the bacterial reactor. Alternatively, if there is a high carbonaceous COD, predigestion to produce biogas and thereby remove COD should be considered before entering the algal bioreactor. CO_2 addition has been shown to enhance algal productivity and reduce the loss of nitrogen through ammonia volatilisation (Park, et al., 2011). At a WWBR facility, the CO_2 produced in the bacterial reactors or anaerobic digester could be reused at the algal reactor to enhance productivity with a low increase in operating cost.

Literature on the use of algal reactors in wastewater treatment has focused on HRAPs or adaptions of these. HRAPs are raceway ponds with a depth of 0.2-1 m, mixed by a paddlewheel. HRAPs may be part of an advanced pond system including primary bacterial treatment through anaerobic digestion, hence precedent for the application of HRAPs in the WWBR context is available (Park, et al., 2011; Rose, et al., 2007). Total COD removal in the order of 31-53% in HRAPs combined with advanced settling ponds has been reported (Rose, et al., 2007).

Alternatively, wastewater effluents high in nitrogen and phosphorous are increasingly being sought as nutrient sources for algal production systems for biodiesel, carbon capture, feed supplements and fertilisers (Louw, et al., 2016). The algal bioreactor or ponding systems is mainly used for low COD, high nitrogen, high phosphorous waste streams. In algal biofuel production, nitrogen and phosphorous nutrient recycling through, for example, recycling the algal residue after oil recovery or the anaerobic digestate after biogas production, back into the system is desirable to maximise bioenergy production. In a WWBR, it is necessary to have a secondary algal product, such as a fertiliser or soil conditioner, to remove nitrogen and phosphorous from the system as this is defined as one of the roles of the algal reactor.

Algal product markets include use for bioenergy either on-site or externally, for animal and aquaculture feed additives, algal dyes and soil conditioners and fertilisers (Griffiths, et al., 2016). Nutraceuticals and food products can only be produced when the waste stream is a suitable precursor for food-based products (e.g. waste stream from a food producing facility). An algal ponding system is not suitable when there are space constraints; HRAPs require 50 times greater land area than activated sludge systems (Peccia, et al., 2013). IBhayi Brewery (SA Breweries, Port Elizabeth) experimented with the interfacing of the anaerobic digester and algal and hydroponic ponding systems, demonstrating constraints for urban breweries (Section 2.7.2). Potential exists to expand algal systems to higher intensity closed photobioreactor systems with higher value products for smaller volume wastes.

3.4.3 Macrophyte bioreactor

The macrophyte reactor is positioned as a polishing step in the WWBR, not as the main focus. It is basically a constructed wetland, which means it is characterised by a large land requirement. However, the macrophyte reactor does not equate to a treatment wetland, where the definition is "wastewater treatment technologies that feature passive biological treatment mechanisms with minimum mechanical energy inputs" (WEF FD-16, 2010). The macrophyte bioreactor is designed and constructed with the focus on effective product removal (Fosso-Kankeu & Mulaba-Bafubiandi, 2014) and compliant exiting water, which is also seen as a product of value. This requires higher maintenance and greater mechanical input to ensure higher productivity. It may approach an agricultural production system.

There are different types of macrophyte bioreactors. The classification is based on hydrology and type of macrophyte growth. There are three possible types of hydrology: open water-surface, horizontal subsurface flow and vertical subsurface flow. Macrophyte growth is usually classified as emergent, submerged, free-floating or floating-leaved. Hydrology and type of macrophyte growth are used in various combinations to achieve different results (Vymazal, 2014).

The treatment efficiencies and bioproduction potential of the different macrophyte bioreactor types all reside in the same order of magnitude. The greatest challenge with the macrophyte bioreactor is efficient harvesting and maintenance. To this end, the floating wetland system shows the greatest potential. The matrix that supports the root growth also serves as baffles and as attachment sites for bacterial growth, thereby increasing the effective surface area and active biomass for increased treatment efficiency (WEF FD-16, 2010). The advantage of the floating matrix, provided that the holding tank or pond does not dry out and allow the roots to embed on the pond floor, is that the sludge removal potential is greatly enhanced as there are fewer obstructions like roots. The floating matrix can be removed entirely and processed externally, while the pond is drained, without excessive harm to the macrophytes, increasing the ease of harvesting of the macrophytic products. The macrophyte bioreactor system is more accessible if the ponds are designed in channels, but this also introduces the greatest weakness of the system: the large capital cost in channel construction as compared with conventional wetland pond systems.

Floating treatment wetlands (FTWs) form another type of macrophyte bioreactor, first developed about 20 years ago in Japan (Dodkins & Mendzil, 2014a). There are several FTWs in operation using a variety of methods to bind the matrix and allow it to float, including bamboo, empty plastic bottles, etc. A commercial design, marketed by Floating Islands International (Floating Island International, 2016), uses post-consumer polymer fibres (Reinsel, n.d.). It is possible for FTWs to be more efficient than conventional constructed wetlands under some circumstances (Dodkins & Mendzil, 2014a).

3.4.4 Solids bioreactor

A major objective of WWBR is decoupling solid and liquid residence time; it is expected that a large amount of wet solids be separated from the incoming liquid stream early in the process, with additional solids separated out in each reactor train.

The solids bioreactor specified for use in a WWBR uses SSF, which is generally defined as the growth of microorganisms on (moist) solid material in the absence or near absence of free water (Pandey, et al., 2010).

In mixed SSF, the microorganisms are various and not fully characterised. Consequently, microbial community characteristics may be used to realise and control the culture conditions and metabolic processes. Aerobic mixed SSF can be divided into co-culture and mixed-culture processes (Pandey, et al., 2010). Co-culture is a process in which a small number of selected and known microorganisms co-exist and drive the process in a concerted manner. Mixed-culture cultivation uses a variety of known or partially known microorganisms grown under conditions not requiring sterilisation such that the microbial community is dynamic, altering to meet the conditions within the system through an ecological approach.

There are several designs of SSF reactors, namely:

1. Static beds without forced aeration (tray bioreactors, Koji type).
2. Static beds with forced aeration (packed beds).
3. Pulsed mixing without forced aeration (discontinuously rotating drum).
4. Pulsed mixing with forced aeration (intermittently stirred beds).
5. Continuously mixed without forced aeration (continuously rotating drums).
6. Continuously mixed with forced aeration:
   a) the rocking drum bioreactor,
   b) the gas-solid fluidised bed,
   c) the continuously stirred aerated bed.
7. Other designs such as the patented periodic air-forced pressure oscillation and the immersion bioreactor, which are based on intermittent immersion in a liquid medium (Couto, et al., 2002; Couto & Sanromán, 2006).

The scale-up of SSF reactors is a bottleneck in the application of SSF. In the bioreactor reaction system, activity is controlled by three major sub-processes: thermodynamics, biokinetics, and heat and mass transfer. The transfer process (mainly mass and heat transfer) is the most important and is a core issue for scale-up (Mitchell, et al., 2010).

It is still uncertain whether the “non-biodegradable organics” in wastewater are biodegradable under the right conditions. Fungal metabolism is different and complementary to bacterial metabolism, and has been shown to degrade recalcitrant chemicals (Chen, et al., 2015; Gouma, et al., 2014). One hypothesis is that a dedicated solid substrate bioreactor oriented towards non-biodegradable organics could improve the characteristics of this fraction, and possibly produce valuable products. Existing research on SSF on municipal sludges is scarce; improved research in this field is strongly recommended.

3.4.5 DSP in the WWBR

DSP and fractional separations are generally well developed for the biotechnology and chemical engineering industries. In the WWBR context, a major cost component is expected to be the product recovery costs. The WWBR needs to be designed with product recovery in mind. This in turn needs integration with the appropriate reactor design (Chapter 6). Conventionally reactor design is focused on maximisation of productivity, and seldom cognisant of a need for reduction in DSP costs.

There is limited work available on DSP specifically for dilute streams. Approaches used in wastewater treatment as well as in mining of specifically low-grade ores give some indication of the requirements. While the processes listed in Tchobanoglous, et al. (2003) are focused on constituent removal, they have already been adapted for the wastewater context. The processes need to be adapted to focus on product recovery as well. Unit operations and processes used to remove constituents found in wastewater (adapted from Tchobanoglous, et al. (2003)) include:

- Suspended solids: Screening, grit removal, sedimentation, high-rate clarification, flotation, chemical precipitation, deep filtration, surface filtration.
- Biodegradable organics: Membrane filtration.
- Nitrogen removal: Air stripping, ion exchange.
- Pathogen removal: Chlorine compounds, chlorine dioxide, ozone; ultraviolet (UV) radiation.
- Colloidal and dissolved solids: Membranes, carbon adsorption, ion exchange.
- Volatile organic compounds (VOCs): Air stripping, carbon adsorption, advanced oxidation.
- Odours: Chemical scrubbers, carbon adsorption, biofilters, compost filters.

Separation and purification processes play a critical role in biorefineries and their optimal selection, design and operation to maximise product yields and improve overall process efficiency. Separations and purifications are necessary for upstream processes and for maximising and improving product recovery in downstream processes (Ramaswamy, et al., 2013).

The first consideration is to increase the product concentration and reduce the total volume by orders of magnitude, i.e. to recover the product. If the product is biomass associated and the biomass can be recovered in high concentration, the biomass can be processed through conventional biotechnological processes. An overview of biomass conversion processes and the separation and purification technologies in biomass biorefineries (adapted from Ramaswamy, et al. (2013)), and their suitability to the WWBR is given below:

- Distillation: Large energy requirement; is not suitable to the bulk stream, may be suitable after initial processing to reduce the total volume.
- Liquid-liquid extraction (LLE): Large solvent use, may reduce the quality of the water. Not recommended on bulk stream, can be feasible for final processing.
- Supercritical fluid extraction: Large energy requirement, may only be suitable for final processing.
- Adsorption: Complex streams may foul the adsorption media, chemically or physically. It may be difficult to find and optimise a suitable adsorption method.
- Ion exchange chromatography: Complex streams may foul the exchange media, chemically or physically. It may be difficult to find and optimise a suitable chromatographic method.
- Simulated moving bed technology for biorefinery applications: May be too technologically complex and difficult to maintain or operate optimally.
- Microfiltration, ultrafiltration and diafiltration: Maintenance may be expensive, need upstream processes to reduce fouling potential.
- Reactive absorption: The complex nature of the wastewater may foul/destroy the absorption surfaces.

Other processes which should be evaluated according to Ramaswamy, et al. (2013) include:

- Nanofiltration.
- Membrane pervaporation.
- Membrane distillation.
- Filtration-based separations in the biorefinery.
- Solid-liquid extraction in biorefinery.
- Membrane bioreactors for biofuel production.
- Extraction-fermentation hybrid (extractive fermentation).
- Reactive distillation for the biorefinery.
- Pressure swing adsorption.

The challenge of DSP for WWBR process streams is a complex combination of the wastewater and bioprocess situations with some unique additional issues predicated on the particular feedstock. Thus, for example, waste streams with a high complexity can present particular difficulties in terms of physical interference in filters and pumps from elements of the waste, such as feathers in poultry abattoir waste or cotton buds in municipal waste. Another example would be the difficulty of flow for high-viscosity waste “waters” such as vinasse. A particular consideration is toxic compounds like heavy metals that bind, for example, to chromatographic columns irreversibly.

3.4.6 Other process considerations for the WWBR

Wastewater is usually a receptacle – meaning the composition and flow rates cannot be controlled, including seasonal variability and changing characteristics over time. This can to some extent be addressed through holding tanks and pretreatment. Ideally, mitigation of this challenge will happen through partnerships and adequate communication with the industries creating the wastewater.

Anaerobic bioreactors have not been directly considered in this report, as this limits the production of lower value biofuel and bioenergy products. Moreover, energy from wastewater is already in relatively common use (Section 2.7) and the technology is well developed. However, this is acknowledged to be an important component of wastewater treatment/valorization, and will be suitable as a pre- or post-treatment step in the context of the WWBR.

Fundamental thermodynamic laws mean that the diffuse nature typical of wastewater remains a challenge that needs consideration. WWBR will not work in all cases, and frequently the compromise for producing product is time. Products take longer to be produced.

3.5 Considerations for Integration into the WWBR

In moving towards the WWBR, the considerations outlined in this chapter must be explored further with awareness of the impact of the interrelationship of unit operations. The principles of industrial ecology dictate that the components of an industrial system are optimised to function as an integrated system, rather than maximised with respect to individual unit productivities (Graedel & Allenby, 2010). These principles are followed with, and within, the WWBR as well. The integration and optimisation of the WWBR into the wider industrial ecosystem has two main aspects from an operational perspective: finding complementary streams to supplement the main wastewater stream for optimal operation and commercial production, and optimising the supporting units to optimise the unit producing the commercially relevant product.

3.5.1 Supplementary raw materials

The successful integration of processes into a WWBR is largely dependent on the availability of appropriate biomass feedstock. Special attention needs to be given to potential seasonality of wastes such as agricultural and food processing by-products. Feedstocks may need to be stored and managed to ensure efficient use of the equipment and controlled and stable deliverables to the market (Fava, et al., 2012). Furthermore, multiple feedstocks may need to be processed on the same plant to enable all-year processing, owing to its major impact on economics.

While conventional wastewater treatment attempts to limit the use of supplementary substrates to reduce treatment cost, it is well-established practice to add reagents to obtain better treatment performance in biotechnology. In the treatment and resource recovery of mine wastewater, sewage sludge is used as electron donor in the BioSure™ process for treating acid mine drainage through biological sulphate reduction. Similarly, excess VFAs (Van Hille, et al., 2015), ethanol and molasses have been used (Buisman, 1995). Crude glycerol, a waste product from biodiesel production has been investigated at length as a supplementary and cheap substrate for bioprocesses (Dobson, et al., 2011). A typical supplementary substrate is methanol (Henze, et al., 2008). The methanol contaminants, methoxide and high pH limit its use for some applications, but it has promise for wastewater addition (Pagliaro & Rossi, 2008) in which these inhibitory components are diluted.

With bioeconomy growing, more biologically suitable waste streams from industrial bioprocesses may become available. While this is currently viewed as a potential limitation of the bioeconomy in terms of efficient resource use, the biological nature of the wastes may contribute to a well-functioning bio-industrial ecosystem (Prasad, 2015).

While the most common additive to wastewater streams is regarding the electron donor (or an organic source), the WWBR may need more sophisticated additives (Ferry & Giljova, 2015; Olguín, 2012), possibly nutrient streams for a more appropriate C:N:P ratio, as would be required for intensive bioproduct formation in bacterial reactors or algal production, or addition of vitamins, co-factors, or specialised substrates like amino acids for biopolymer production. From a cost and complexity perspective, the need for such additives should be minimised, but from a WWBR perspective this should nonetheless be considered as an option. In particular, the sourcing of complex waste streams rich in these supplements may be appropriate.

It is tempting to design an eco-industrial park to tailor for the effective use of waste streams. From an industrial ecology perspective; however, designing co-placement of industries to provide complementary waste streams (greenfield development) has proven to be less successful than shaping processes (and products) in response to the existing streams and potential synergies (brownfield development) (Desrochers & Sautet, 2008).

3.5.2 Optimising for the main economic unit

Overall process optimisation is a key factor with focus on both the economic product and the water product. The range of unit operations, type of microorganisms, catalysts, conversion efficiency, yield and productivity, among others, significantly affect the overall sustainability and economic aspects of a WWBR. The WWBR has the dual objective of water treatment and bioproduction. While the WWBR differs on a case-by-case basis, it is likely that one unit will be more intensively optimised for bioproduction. The other unit(s) will either contribute products to improve the operation of the economically relevant unit or provide secondary products. In either case, these supplementary units will have water treatment as their main optimisation criterion.

This approach already exists in bioproduction. For example, the bacterial production of VFAs to improve algal biomass growth where the algal unit is the main focus (Rose, et al., 2007), or the use of anaerobic digestion to provide VFAs for biological sulphate reduction–sulphide oxidation to yield a sulphur product (Van Hille et al., 2015). In the WWTW, a similar interactive effect is obtained at the Johannesburg Water Northern Works detailed in Section 2.7.3. (Franks, et al., n.d.) where the heat energy from the CHP units is used to optimise biogas production by preheating the sludge entering the anaerobic digestion units. This has the knock-on effect by improving the quality (and therefore value) of the digestate. Several of the biogas production units installed by municipalities in the Western Cape (see Table 19) (Ferry & Giljova, 2015) combine waste streams (most frequently municipal solid waste and sewage) to optimise the feedstock for the anaerobic digestion units.

Within the WWBR, there are numerous possible synergies between products and processes. Anaerobic digestion can be used as pretreatment to hydrolyse complex molecules. The macrophyte biomass, in particular the fibres, could be used to support fungal growth in the solid substrate reactor. Algal and macrophyte reactors can be used to scavenge nitrogen and phosphorous. Of course, energy (heat and/or electricity) can be used to fuel the WWBR. It is imperative that the dual focus of economic and environmental perspectives is always maintained.

3.5.3 The wider perspective

From a wider social perspective, several factors need to be in place for WWBR to be a viable option. These include a policy of treating wastewaters to recover nutrients simultaneously with producing clean water for reuse, as well as public approval of products-from-waste together with reuse of water.

It is beneficial to recognise the environmental need in the industrial sector and the economic benefit of the WWBR. For wastewater to be used in a WWBR, the volume, composition, geographic location and seasonality complexity must be known. Due to South Africa's aging infrastructure and lack of investment in the water and wastewater sector, PPPs boosting innovation in this space have potential. Relationships between new and old technologies can be created with a variety of role players in this field. Particularly, the redefinition of facilities to derive economic benefit while meeting water quality standards is expected to encourage investment. Evaluation of the potential products obtained from wastewater, their position in the value chain and their relevance within the South African economy is essential.

The process considerations of a WWBR in terms of the social and ecological niche, unit operations and DSP must have a synergetic relationship for considering the integration into a WWBR. According to the Brazilian Bioethanol Science and Technology Laboratory (CTBE, n.d.), integrated evaluations of biorefineries should include: optimisation of concepts and processes, consideration of the different facets of sustainability, and analysis of the status of developing technologies. The integration of these factors is demonstrated in Figure 8.

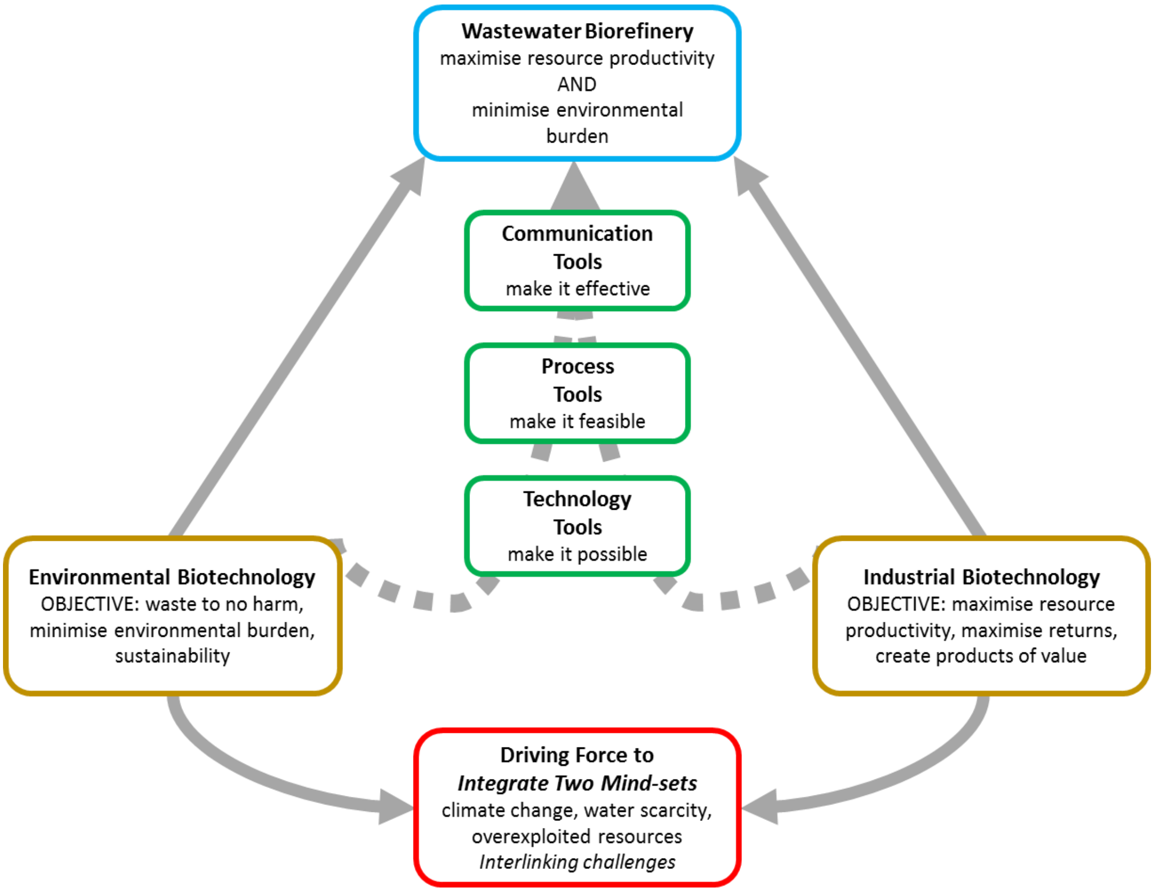


Figure 8: Integration of industrial and environmental technologies for emerging WWBRs

4 REVIEW OF POTENTIAL WASTEWATER BIOREFINERY FEEDSTOCK: SOUTH AFRICAN WASTEWATER STREAMS

This chapter reviews wastewater burdens and resources within South Africa. Wastewater from both industrial sources and municipalities are considered. Multiple sources, which were used to compile the data presented, are noted. Where data could not be found, estimations were used and noted. Where data was unavailable, even for estimations, the stream is listed without data. Supplementary data, sources and calculations are presented in Appendix C.

The source data exists in a variety of forms. Mostly, the data has been given in terms which translate easily to environmental impact rather than measures of suitability for valorization. The data available is used to determine annual volumes and regional distribution. The carbon, nitrogen and phosphorus composition of these wastewater types allow suitability for use as feedstock for WWBRs to be assessed. Where possible, known complexities have been mentioned. A number of wastewaters have been examined in more detail, which is presented in Section 4.2.

This chapter, supported by the accompanying appendix, is intended to inform the consideration of the potential of wastewater in South Africa as a source of valuable nutrients to produce biobased products by drawing on specific wastewater examples. This consideration should be combined with concern for the potential within the wastewaters for remediation of clean water that complies with legislation. The data presented here is therefore seen as offering a first-order estimation of WWBR potential.

4.1 Reviewing Previous Studies on Wastewater in South Africa

The major sources of information used for this report are Burton et al. (2009), Cloete et al. (2010) and several other WRC reports, including the NatSurv reports (WRC, 2015b), together with personal communications with staff at the WRC. Other information is obtained from a selection of journal articles, South African institutions and South African academic theses.

The feasibility study compiled by Burton et al. (2009) centred on the potential for energy from wastewater. From the analyses conducted, the volumes and COD content of wastewaters from several industries and municipal WWTWs was provided. Cloete et al. (2010) created a first-order inventory of water use and effluent production by the South African industrial, mining and electricity generation sectors. Unfortunately, the data used to complete these reports were not all recent at the time of publication and therefore much of it is now outdated.

The NatSurv reports published by the WRC are summarised in Table 24. This data is largely outdated. A new cycle of NatSurv reports are currently in preparation or under review for publication. Information from the WRC obtained through correspondence suggests that the following updated NatSurv reports will be published: Metal Finishing Industry in February 2016, Dairy Industry in March 2016, Brewery Industry in May 2016, Steel Industry and Pulp and Paper Industry in September 2016. These were not available sufficiently early to be included in this report. In 2017, reports for laundry, edible oil and abattoir/red meat are expected.

The Green Drop initiative of the DWS has reported the performance of municipal, public and private WWTWs. It is an incentive-based model to identify, reward and rectify non-compliance in the water sector. It supplies information pertaining to the volumes of wastewater entering the WWTWs nationally and gives an indication of the sizes of these WWTWs (DWS, 2014).

Table 24: NatSurv reports from the WRC

Report	Report number	Year of publication	Title	Revised report number	Year of new report publication
NatSurv 1	TT 29/87	1986	Water and wastewater management in the malt brewing industry	–	May 2016
NatSurv 2	TT 34/87	1987	Water and wastewater management in the metal finishing industry	TT 644/15	January 2016
NatSurv 3	TT 35/87	1987	Water and wastewater management in the soft drink industry	TT 640/15	October 2015
NatSurv 4	TT 38/89	1989	Water and wastewater management in the dairy industry		March 2016
NatSurv 5	TT 39/89	1989	Water and wastewater management in the sorghum malt and beer industry		May 2016
NatSurv 6	TT 40/89	1989	Water and wastewater management in the edible oil industry		2017
NatSurv 7	TT 41/89	1989	Water and wastewater management in the red meat industry		2017
NatSurv 8	TT 42/89	1989	Water and wastewater management in the laundry industry		2017
NatSurv 9	TT 43/89	1989	Water and wastewater management in the poultry industry		2017
NatSurv 10	TT 44/90	1989	Water and wastewater management in the tanning and leather finishing industry		
NatSurv 11	TT 47/90	1990	Water and wastewater management in the sugar industry		
NatSurv 12	TT 49/90	1990	Water and wastewater management in the paper and pulp industry		September 2016
NatSurv 13	TT 50/90	1993	Water and wastewater management in the textile industry		
NatSurv 14	TT 51/90	1993	Water and wastewater management in the wine industry		
NatSurv 15	TT 180/05	2005	Water and wastewater management in the oil refining and re-refining industry		
NatSurv 16	TT 240/05	2005	Water and wastewater management in the power generating industry		

4.1.1 Compiling data on wastewater in South Africa

As a quick reference for readers, the relationships found in literature for calculating the approximate amount of wastewater generated for several industries in South Africa are shown in Table 25. This information with other information mentioned to calculate effluent volumes were not readily available.

Table 25: Examples of relationships calculating the amount of wastewater for different industries

Industry	Relationship	Reference
Brewing	6 m^3 water consumed/m^3 beer produced 4-8 ℓ water consumed/ℓ beer produced 3-5 ℓ wastewater generated/ℓ beer produced	(CSIR, 2010) (IWA, 2009)
Dairy	15-51 ℓ wastewater /cow/day Pasteurised milk: wastewater 85-90% of water intake Butter and cheese: wastewater 90-95% of water intake Milk powder and condensed milk: wastewater >100% of water intake	(Du Preez, 2010) (Steffen, Robertson and Kirsten Inc, 1989a)
Fishery	11 m^3 H_2O consumed/t fish processed Large salmon processing: 3.12 ℓ wastewater generated/kg fish Small salmon processing: 9.90 ℓ/kg fish Canning of tuna and sardines: 14-22 ℓ/kg	(Quiroz, et al., 2013) (Chowdhury, et al., 2010)
Petroleum	0.1-5 m^3 wastewater generated/t crude oil	(Burton, et al., 2009)
Poultry abattoir	15-20 ℓ/bird influent wastewater 80-85% of water intake	(CSIR, 2010) (Bremner & Johnston, 1996)
Pulp and paper	33-136 m^3/t integrated plant 1-49 m^3/t pulp and paper products 150 t wastewater/1 t paper produced wastewater 85% of water intake	(CSIR, 2010) (Hagelqvist, 2013) (Macdonald, 2004)
Red meat abattoir	m^3/wrcu (1) 818 ℓ wastewater per slaughter unit (2) wastewater 85% of water intake	(CSIR, 2010) (Neethling, 2014) (DWA, 2001)
Soft drink	2.7 m^3 water/m^3 soft drink influent Carbonated drinks: 1.6 ℓ wastewater/ℓ product Fruit juice: 2.2 ℓ wastewater/ℓ product	(CSIR, 2010) (Pollution Research Group, 2015)
Sugar	30-100 m^3 water consumed/100 t of cane processed (average of 60 m^3/100 t) 18 m^3 wastewater generated/100 t of sugarcane processed 0.75-1.5 Mℓ wastewater/day – is approximately 30% of the water intake	(Steffen, Robertson and Kirsten Inc., 1990) (CSIR, 2010) 30-100 m^3/t cane processed
Textiles	Specific water intake: 95-400 ℓ/kg 70-80% of H_2O consumed is expelled as wastewater	(Steffen, Robertson and Kirsten Inc., 1993)

Industry	Relationship	Reference
Wine making	700-3800 ℓ/t of grapes 1.8-6.2 ℓ/ℓ absolute alcohol – spirit distillation 1-4 ℓ wastewater/ℓ wine	(CSIR, 2010) (Welz, et al., 2015))

(1) wrcu – the number of non-bovine species equivalent to one bovine cattle unit in terms of water usage during processing. One bovine cattle is equivalent to two calves, six sheep, six goats or 2.5 pigs (NatSurv 4, 1989)

(2) The waste per slaughter unit according to Neethling (2014) is 818 ℓ of effluent and 31 kg of solid waste. A slaughter unit is based on weight and may be equivalent to one cow, bull or ox; two calves; one horse; six sheep or goats; four porkers; two baconers or one sausage pig

The data collected on wastewaters offered significant challenges in developing a complete and consistent dataset. Data available was presented in different units, collected by different methods and, in many cases, a range of parameters was not measured. In this study, first-order approximations were used to provide estimates where data could not be sourced. The aim was to provide a uniform approach to present relevant data (Section 3.2.2), including:

- Annual volumes produced with site-specific data, in terms of volumes per day, indicating the distribution of available streams.
- Concentrations of carbon, nitrogen and phosphorous present in the wastewater indicating potential for recovery.
- Indicators of handling issues: pH and conductivity.
- Noted complexities: solids, toxic compounds, metals, complex organics and other valuable components.

One potential approach is to find specific effluent volume (SEV) produced per unit, and the annual production (either per site or per region). These values can be used to estimate expected annual production, while also being used to analyse discrepancies in data. Such discrepancies may result from outdated data or be due to cleaning and other periodic, non-unit specific operations. Where there are large discrepancies, the source of the difference must be found. The data presented in this report provides a sample of the data required to develop the requisite water database as well as an approach to its collation. In addition to developing a database for water professionals, it will be useful to develop a tool (such as an Excel™ sheet or visual aid) to allow the greater community to contribute to the data collection.

In addition, validation of the data and its analysis on a national, provincial and local basis are essential for assessing the potential to derive value from the wastewaters where the regional and local distribution of the resource is critical in determining practicality of its beneficiation.

The composition data of major wastewater sources in terms of COD, NO_3^- or NO_2^- or NH_4^+ or total Kjehldahl nitrogen (TKN) or total nitrogen (TN) and PO_4^{3-} have been compiled from a selection of references (shown in summary form in Appendix C.2). In cases where the COD, nitrogen and phosphorous contents of a particular stream are not given, approximations have been used based on literature findings. From the capacity and composition data, the amount of carbon, nitrogen and phosphorous that can be recovered from these industries is given.

This report does not deal with the specifics of the manufacturing process but only focused on the wastewater effluent that is generated from the process before it is either treated or disposed of in municipal sewers. It is essentially a black box considering only water input to process and wastewater generation. Cleaning agents used in these industries and that form part of the composition of the effluents are not considered. It is assumed that cleaning agents used in the food and beverage industries are biodegradable.

4.1.2 Approach to data standardisation

Most volumes are given on an annual basis. In order to classify these flows according to the capacity of wastewater treatment in terms of volume per day, it was assumed that 365 days are used. All flows are reported as Mℓ/day. Using the categories that are specified in the Green Drop Report for municipal wastewater (DWS, 2014), the capacity of each wastewater stream is further classified as micro (<0.5 Mℓ/day), small (0.5 to 2 Mℓ/day), medium (2 to 10 Mℓ/day), large (10 to 25 Mℓ/day) and macro (>25 Mℓ/day). The number of these streams or plants in operation in each industry is also useful data.

In some cases, the data collected was detailed and gave a good indication of the industry. However, only average data could be used in several cases.

In order to standardise to concentrations of carbon, nitrogen and phosphorous, the conversions from the COD, TKN/ammonia/nitrate/nitrites and PO_4^{3-} found in literature were calculated as follows (details in Appendix C.1):

- Concentration of carbon (mg/ℓ) = 3 × COD (mg/ℓ).

- Concentration of N (mg/ℓ) = (14/62) × NO_3^--N (mg/ℓ) or
  (14/46) × NO_2^--N (mg/ℓ) or
  (14/18) × NH_4^+-N (mg/ℓ).
  The TKN is the sum of organic nitrogen, NH_3, and NH_4^+ in the sample. Organic nitrogen consists of protein, urea and nucleic acids.
  The TN is the sum of TKN, NO_3^--N and NO_2^--N.

- Concentration of phosphorous (mg/ℓ) = (31/95) × PO_4^{3-} (mg/ℓ).

4.1.3 Identifying the valorization potential of South African wastewater

In South Africa, the water supply is divided as follows: agriculture receives about 60%, environmental use 18%, urban and domestic use 11.5%, mining and industrial use 10.5% (Rand Water, n.d.). This report focuses on the municipal and industrial effluents produced in South Africa.

The annual effluent production volumes from these industries, collected from the same literature sources, and their potential carbon, nitrogen, and phosphorous contributions as calculated by the authors are summarised in Table 26. This is a summary of the data that is presented later in this chapter where a number of these wastewater categories are discussed and characterised in more detail (Section 4.2 and Section 4.3).

Table 26: Annual effluent production and the potential carbon, nitrogen and phosphorous contribution in several South African industries (detailed data is provided in Appendix C.2.1)

Industry Sector	Mℓ Effluent/ Year	Estimated Tonne C/Year	Estimated Tonne N/Year	Estimated Tonne P/Year	Comment	Reference
Municipal	1 825 000	4 653 750	118 625	28 288		(Henze, et al., 2008)
Abattoir (poultry)	5 400	71 280	945	308	Blood, skin, fat, viscera, faeces, significant solid waste	(Molapo, 2009)
Abattoir (red meat)	8 188	139 057	101	nl	Blood, skin, fat, viscera, faeces, significant solid waste	(DWA, 2001)
Brewing	8 334	100 008	438	250		(Burton, et al., 2009) (Brito, et al., 2007)
Canning	1 074	11 599	nl	nl		(Binnie and Partners, 1987a)
Cleaning and cosmetics	314.3	5 003	11.7	5.64		(Cloete, et al., 2010)
Dairy	86 393	3 900 000	30 238	3 456	Fats, protein, faeces, grit	(Du Preez, 2010)
Distillery (alcoholic beverages)	386.8 (#)	128	428	nl		(Melamane, et al., 2007)
Dyeing and colouring	645	2 137	nl	nl	Alkaline pH, toxic organic residues, high NaCl concentration (1590 mg/ℓ)	(Cloete, et al., 2010)
Edible oil	1 361	543 039	42.2	3 409	Pollutants such as fats, oils and grease (FOG), sodium, sulphates and phosphates	(Roux–Van der Merwe, et al., 2005) (Surujlal, et al., 2004) (Steffen, Robertson and Kirsten Inc., 1989b)
Fishery	1 760	30 624	62	nl	Flesh, scales, blood	(Chowdhury, et al., 2010) (Quiroz, et al., 2013)
Laundry	218.6	564	0.07	2	Solvents, surfactants	(Cloete, et al., 2010)
Petroleum	77 380	1 830 000	3 691	101	Oil and grease, phenols	(Gasim, et al., 2012)

Industry Sector	Mℓ Effluent/ Year	Estimated Tonne C/Year	Estimated Tonne N/Year	Estimated Tonne P/Year	Comment	Reference
Pulp and paper	339 300	967 005	3 068	443	Adsorbable organic halogen (AOX), dioxin, chlorinated organics	(Cloete, et al., 2010)
Soft drinks	4 070	74 326	nl	nl		(Pollution Research Group, 2015)
Sugar	411	2 158	nl	nl	Fibres, sand	(Mooij, et al., 2015)
Textiles	0.03 million	0.454 million	15	196	Azo dyes	(Cloete, et al., 2010) (Steffen, Robertson and Kirsten Inc., 1993)
Winery	2 421	49 388	266	126	Polyphenols, inorganics such as sodium and potassium	(Welz, et al., 2015) (Cai, et al., 2013) (Brito, et al., 2007)

Assumed from distillery production data (SAWIS, 2016) and assuming an SEV of 2.5 ℓ effluent/ℓ wine produced
nl not listed

4.2 Overview of Municipal Wastewater in South Africa

Municipal wastewater usually includes considerable amounts of discharged industrial effluent. Examples of the top industrial effluent producers within some metropolitan areas are shown Table 27. Due to confidentiality, no company names were mentioned in the Cloete, et al. (2010) report.

Table 27: Examples of top industrial effluent discharge into municipal wastewater (Cloete, et al., 2010)

Amathole	44% automotive	41% food manufacture	15% textiles			
Cape Town	30% brewery *	29% textiles	18% paper and paper products	13% food manufacture	10% beverage	
Johannesburg	34% yeast	17% beverage	15% electroplating	13% dairy	12% food manufacture	9% automotive
eThekwini	58% paper and paper products	18% petroleum and petroleum products	15% textiles	9% beverages		
Nelson Mandela	42% brewery	21% automotive	12% textiles	9% food manufacture	8% dairy	8% tannery
Tshwane	81% brewery	11% food manufacture	8% textiles			

* standalone WWTW installed

From the Green Drop Report (DWS, 2014), the status of municipal wastewater treatment in South Africa of 152 municipalities and 824 plants were assessed, as shown in Appendix C.3. The total amount of wastewater entering these works is approximately 5000 Mℓ/day or 1 825 000 Mℓ/year (365-day operation). There are also five privately owned WWTWs with a total treatment capacity of 106 Mℓ/day. This combined value (5106 Mℓ/day) of wastewater going into the WWTWs is comparable to the estimate obtained by Burton, et al. (2009) of 7600 Mℓ/day. The volume, concentration and complexity data for South African municipal WWTWs is shown in Table 28.

Municipal wastewater differs from most industrial wastewater regarding complexity, variability and dilution. The range of concentrations of COD, TN and total phosphorous (TP) reported by Henze, et al. (2008) was used as a first estimate. The COD ranged from 500 to 1200 mg/ℓ, TN from 30 to 100 mg/ℓ and TP from 6 to 25 mg/ℓ. This can be converted to 1500-3600 mg C/ℓ, 30-100 mg N/ℓ and 6-25 mg P/ℓ. The pH ranged between 7 and 8; the total suspended solids (TSS) from 250-600 mg/ℓ (Appendix C.3).

Table 28: Volume, concentration and complexity data for the South African municipal wastewater treatment industry (detailed data and references of data sources are provided in Appendix C.3)

Effluent volume in South Africa	**Total estimated effluent volume in South Africa**	*Mℓ/year*	1 825 000
	Days of operation	*days*	365
	Total estimated effluent volume in South Africa	*Mℓ/day*	5 000
Cross-reference	**To worksheet with primary data and calculations**		Appendix C.3
Distribution: number of plants	**TOTAL**		**828**
	Micro	*<0.5 Mℓ/day*	168

	Small	*0.5-2 Mℓ/day*	269
	Medium	*2-10 Mℓ/day*	232
	Large	*10-25 Mℓ/day*	65
	Macro	*>25 Mℓ/day*	62
Concentration	**Estimated average carbon content**	*mg/ℓ*	2 550
	Estimated average nitrogen content	*mg/ℓ*	65
	Estimated average phosphorus content	*mg/ℓ*	15.5
	pH		7-8
	Conductivity	*mS/m*	70-120
Complexities **Present. The compounds will differ per municipal WWTW*	**Solids component**		Present*
	Toxic compounds		Present
	Metals		Present
	Complex organics		Present
	Other valuable components		Present

4.3 Overview of Industry-specific Wastewaters in South Africa

In terms of effluent production processed outside of municipal water treatment plant, a total industrial effluent of 69 Mm^3/year (69 000 Mℓ/year) is generated according to Cloete, et al. (2010). These effluents are summarised in Table 29. The largest industrial wastewater producers in South Africa are the pulp and paper (42%) and petroleum (25%) industries, with mining (10%) and power generation (7%) as the other major consolidated wastewater producers. Although mining wastewater poses the greatest potential risk of all industrial sectors (Cloete, et al., 2010) and has been studied in terms of both bioremediation and valorization (Harrison, et al., 2014), it has been excluded from this report as it is examined in detail in numerous reports published in the WRC "Mine Water" category (WRC, 2016b). Furthermore, mine wastewater is typically low in carbon, nitrogen and phosphorous, the resources on which this study is focused. Similarly, the wastewater from the power generation industry, which Cloete, et al. (2010) place third in terms of risk, has not been included in the evaluations because the components and likely remediation and valorization pathways differ from the generalised wastewaters considered here.

Table 29: Proportion of industrial wastewater by industry sector (Cloete, et al., 2010)

Sector	Effluent Volume%	Comments
Power generation	7%	*Not evaluated*
Mining industry	10%	*Not evaluated*
Pulp and paper industry	42.0%	
Petroleum industry	25.5%	
Food and beverage industry	8%	Animal-based and plant-based
Other Industries	7.5%	Organics-based and non-organics-based

For the implementation of WWBR, the specific site or regional information is more important than the national values. The value that can be expected in terms of WWBRs differs for different scales of industry. Large, standardised plants gain from economy of scale, and usually have to comply with industry water use standards. Small "backyard" industries are not regulated and do not have significant water savings practices in place. The smaller industries are valuable, however, and have high potential in the WWBR space as they may be much more flexible in catering to a niche industry market need. The values examined in the following summaries are for larger industries where information is more readily available. It is anticipated that the smaller industries will have larger effluent values per unit, but the nutrient concentrations may be more dilute.

The pulp and paper industry and the petroleum industry are both large centralised industries and together produce nearly 70% of the industrial wastewater in South Africa. These are therefore high priority in terms of evaluating WWBR potential. The food and beverages industry, given by Cloete et al. (2010) as second after mining in terms of effluent risk, is evaluated in two subdivisions of animal-based and plant-based food and beverages because of the very different components present. Wastewaters of other industries can be divided into organic-based and non-organic-based, and the latter division is not considered for this report.

4.3.1 Pulp and paper industry

According to Hagelqvist (2013), an estimated 400 million tonnes of paper and paperboard was produced globally in 2012 with an estimated 30 to 90 billion tonnes of wastewater produced concomitantly. This equates to 150 tonnes (or 0.15 Mℓ) wastewater generated for every tonne of paper produced. From the CSIR (2010) report, the specific water intake is given as 33-136 m^3/tonne (0.033-0.136 Mℓ/tonne) for an integrated plant and as 1-49 m^3/tonne (0.001-0.049 Mℓ/tonne) for pulp and paper products. This wastewater is deficient in phosphorous and nitrogen in terms of use as substrate for microorganisms, hence components may need to be supplemented in biological treatment.

The major producers in the pulp and paper sector are Kimberly-Clark, Mondi South Africa, Mpact, Nampak and Sappi (PAMSA, 2012a). In 2014, the total pulp and paper production in South Africa was 1 967 000 tonnes and 2 262 000 tonnes respectively (PAMSA, 2015). Therefore, to produce 2.3 million tonnes of paper, approximately 0.34 million Mℓ/year of wastewater is generated from the relationship of 0.15 Mℓ wastewater/tonne paper. Data used in Burton et al. (2009) (Appendix C.4.1) and Cloete et al. (2010) reported 111 971 Mℓ/year (0.11 million Mℓ/year) and 39 488 Mℓ/year (0.039 million Mℓ/year) of effluent respectively produced in this sector. According to MacDonald (2004), approximately 85% of water consumed in the pulp and paper industry is expelled as wastewater.

The COD values reported ranged from 700 mg/ℓ to 1200 mg/ℓ (2100-3600 mg C/ℓ) (Cloete, et al., 2010) while Burton et al. (2009) reported an average of 700 mg/ℓ COD (2100 mg C/ℓ) (Appendix C.4.1). The ammonia and nitrite/nitrate concentrations of the pulp and paper effluent in Tshwane are 8.7 mg/ℓ (8.7 mg N/ℓ) and 1.52 mg/ℓ (0.343 mg N/ℓ) respectively (TN is the sum of these values, and is 9.04 mg N/ℓ) while the phosphate is 4 mg/ℓ (1.305 mg P/ℓ) (Cloete, et al., 2010). This is less than the general limits for wastewater treatment standards of South African effluent according to the General Authorisation Standards (DWA, 2013) listed in Table 21. The average pH ranges between 6 and 8 and does not pose a serious threat to the environment. The TSS do pose a threat with levels as high as 6000 mg/ℓ. Table 30 illustrates the volume, concentration and complexity data for wastewater of the South African pulp and paper industry.

The pulp and paper sector uses large amounts of lignocellulosic material and water during the manufacturing process. The process releases chlorinated lignosulphonic acids, chlorinated resin acids, chlorinated phenols and chlorinated hydrocarbons in the effluent. Approximately 500 different chlorinated organic compounds have been identified, such as chloroform, chlorate, phenols, catechols, guaiacols, furans, dioxins, syringols, vanillins to name a few (IWA, 2009). These compounds are formed as a result of a reaction between residual lignin from wood fibres and chlorine/chlorine compounds used for bleaching. Coloured compounds and AOX released from pulp and paper mills into the environment pose serious threats to aquatic organisms (IWA, 2009).

Table 30: Volume, concentration and complexity data for the South African pulp and paper industry (summarised from Appendix C.4.1)

Effluent volume in South Africa	**Total estimated effluent volume in South Africa**	*Mℓ/year*	339 300
	Days of operation	*days*	365
	Total estimated effluent volume in South Africa	*Mℓ/day*	929.6
Cross-reference	**To worksheet with primary data and calculations**		Appendix C.4.1 – Pulp and paper industry (Section 4.3.1)
Distribution: number of plants (data obtained from Burton et al. (2009))	**TOTAL**		**18**
	Micro	*<0.5 Mℓ/day*	0
	Small	*0.5-2 Mℓ/day*	8
	Medium	*2-10 Mℓ/day*	3
	Large	*10-25 Mℓ/day*	2
	Macro	*>25 Mℓ/day*	5
Concentration	**Estimated average carbon content**	*mg/ℓ*	2 850
	Estimated average nitrogen content	*mg/ℓ*	9.04
	Estimated average phosphorus content	*mg/ℓ*	1.30
	pH		6-8
	Conductivity	*mS/m*	105-348
Complexities	**Solids component (TSS)**	*mg/ℓ*	6 000
	Toxic compounds		AOX
	Metals		-
	Complex organics		Chlorinated lignosulphonic acids, chlorinated resin acids, chlorinated phenols and chlorinated hydrocarbons. Chlorinated organics such as chloroform, chlorate, phenols, catechols, guaiacols, furans, dioxins, syringols, vanillins
	Other valuable components		Cellulose

4.3.2 Petroleum refineries and petroleum products industry

South Africa has four crude oil refineries (Engen, SAPREF, Natref and Chevron), and coal-to-liquid (Sasol) and gas-to-liquid operations (PetroSA, Sasol). Combined they process the crude-oil equivalent of 703 000 bbℓ/day (83 165 tonnes/day). The production capacity of each refinery is shown in Appendix C.4.2. It is assumed that approximately from 0.1 m^3 to 5 m^3 of wastewater is generated per tonne of crude oil processed (Burton, et al., 2009). Using this relationship, it can be calculated that the average wastewater produced is approximately 212 Mℓ/day (0.077 million Mℓ/year). All six refineries have macro-scale WWTWs (<25 Mℓ/day). This wastewater is generated from several sources in the refineries such as during desalting of crude oil, stream stripping, product fractionators, reflux drum drains, hydro-skimming, hydro-cracking, sour water, condensate, boiler blowdown and other sources during the process not directly involved in processing such as water runoff and sewage from the site (Burton et al., 2009; Diya'uddeen et al., 2011). The volume, concentration and complexity of wastewater in the South African petrochemical industry is shown in Table 31.

Burton et al. (2009) report only the COD value from crude oil refineries and values given as 236 to 800 mg/ℓ (708-2400 mg C/ℓ). A COD value of 2036-7052 mg/ℓ (6108-21 156 mg C/ℓ) and an ammonia value of between 303-834 mg/ℓ (236-649 mg N/ℓ) was reported by Pearce and Whyte (2005). The COD value according to Gasim, et al. (2012) of a petroleum refinery wastewater is 7896 mg/ℓ (23 688 mg C/ℓ). The ammonia, nitrate and TKN concentrations are 13.5, 2.23 and 40.6 mg/ℓ (10.5, 0.50 and 40.6 mg N/ℓ) respectively, while the phosphate is 10.2 mg/ℓ (3.33 mg P/ℓ) (Gasim, et al., 2012). The pH value ranged from 4.2 to 9.1 (Pearce & Whyte, 2005). The oil content in petroleum wastewater was determined to be between 124 and 171 mg/ℓ (Pearce & Whyte, 2005). Due to the large variability in the COD and nitrogen concentrations, further information is required from the industry in terms of how these compositions differ from crude oil refineries, coal-to-liquid and gas-to liquid operations.

Table 31: Volume, concentration and complexity data for the South African petroleum industry (summarised from Appendix C.4.2)

Effluent volume in South Africa	**Total estimated effluent volume in South Africa**	*Mℓ/year*	77 380
	Days of operation	*days*	365
	total estimated effluent volume in South Africa	*Mℓ/day*	212
Cross-reference	**To worksheet with primary data and calculations**		Appendix C.4.2
Distribution: number of plants	**TOTAL**		**6**
	Micro	*<0.5 Mℓ/day*	
	Small	*0.5-2 Mℓ/day*	
	Medium	*2-10 Mℓ/day*	
	Large	*10-25 Mℓ/day*	
	Macro	*>25 Mℓ/day*	6
Concentration	**Estimated average carbon content**	*mg/ℓ*	23688
	Estimated average nitrogen content	*mg/ℓ*	47.7
	Estimated average phosphorus content	*mg/ℓ*	1.30
	Ph		4.2-9.1
	Conductivity	*mS/m*	63-1364
Complexities	**Solids component**		Oils and grease
	Toxic compounds		Phenols, sulphides
	Metals		Heavy metals
	Complex organics		Solvents
	Other valuable components		

4.3.3 Animal-based food industry

Using the industrial categories reported across several sources (Burton, et al., 2009; Cloete, et al., 2010; WRC, 2016a), this sub-sector includes poultry abattoirs, red meat abattoirs, fisheries and dairies. Each of these is considered in some detail in the following subsections. While substantial wastewater is generated in some divisions of animal husbandry, especially where animals are raised in high-density conditions within structures such as piggeries, we do not consider this area here.

The animal-based food sub-sector uses large quantities of water because of the stringent cleanliness requirements. The wastewater for all divisions contains high-complexity organics, fats and oils and a considerable amount of solids. Cleaning and sterilisation is an important part of the processing and these products appear in the wastewater but are not considered in this report.

Poultry abattoirs

Abattoir wastewaters are highly complex and fairly variable with a nutrient-rich composition. They also pose a high health risk (Steffen, Robertson and Kristen Inc., 1989c). In South Africa, approximately 46% of the high-throughput poultry abattoirs render blood waste into several kinds of by-products (carcass meal, feather meal, poultry oil and blood meal) as opposed to direct disposal. The most commonly identified blood waste disposal methods include land application (3.8%), municipal sewer (7.6%), sold to contractors (11.5%), burial (34.6%), and rendering (46.1%). Rendering is a heating process for meat industry waste products whereby fats are separated from water and protein residues to produce edible lards and dried protein residues. Commonly it includes the production of a range of products of meat meal, meat-cum-bone meal, bone meal and fat from animal tissues (FAO UN, 1996). Although rendering produces by-products, it is also classified as a disposal method. Effluent from rendering plants contains very high loads of organic matter, therefore it is regarded as a further source of contaminating effluent (Appendix C.4.3) (Molapo, 2009). An estimated 15 ℓ to 20 ℓ of water is required per bird in poultry abattoirs (Steffen, Robertson and Kristen Inc., 1989c). The volume of water discharged as wastewater may amount to between 80% and 85% of the waste load (Bremner & Johnston, 1996). The slaughtering and operational status of these plants (26 abattoirs) is given in Appendix C.4.3 along with the composition of poultry abattoir effluent characteristics found in literature and the volume of wastewater generated (Molapo, 2009). This is summarised in Table 32. Poultry abattoir wastewater is contaminated with fat, viscera, blood, feathers and faeces. It can be characterised and distinguished from other industrial wastewater by its high organic matter, oil and grease and solid content.

Table 32: Volume, concentration and complexity data for the South African poultry abattoir industry (summarised from Appendix C.4.3)

Effluent volume in South Africa	**Total estimated effluent volume in South Africa**	*Mℓ/year*	5400
	DAYS of operation	*days*	365
	Total estimated effluent volume in South Africa	*Mℓ/day*	14.8
Cross-reference	**To worksheet with primary data and calculations**		Appendix C.4.3
Distribution: number of plants	**TOTAL**		**26**
	Micro	*<0.5 Mℓ/day*	1
	Small	*0.5-2 Mℓ/day*	16
	Medium	*2-10 Mℓ/day*	3
	Large	*10-25 Mℓ/day*	6
	Macro	*>25 Mℓ/day*	0
Concentration	**Estimated average carbon content**	*mg/ℓ*	13 200
	Estimated average nitrogen content	*mg/ℓ*	175
	Estimated average phosphorus content	*mg/ℓ*	57.1
	pH		7.0-7.2
	Conductivity	*mS/m*	nl
Complexities	**Solids component**		Fat, viscera, blood, feathers and faeces
	Toxic compounds		–
	Metals		–
	Complex organics		Fats, oils, protein
	Other valuable components		Feathers (keratin)

Valorizing wastewater from abattoirs needs to take advantage of the high fat content. Fungal products may be particularly well suited here, integrated with energy recovery in the form of biodiesel. Biogas production through anaerobic digestion may be less effective due to the high fat content; however, anaerobic digestion for waste treatment at poultry abattoirs has been reported recently (Molapo, 2009). An installation at RCL Foods Worcester Poultry Processing in the Western Cape is being constructed and commissioned during 2016 for concomitant biogas production for electricity generation for the RCL facilities and remediation of wastewater to reduce the COD load by 80% (Worcester Standard, 2016).

Red meat abattoirs

The "Guidelines for the Handling Treatment and Disposal of Abattoir Waste" (DWA, 2001) reported that the red meat industry comprises 285 abattoirs. The annual water consumption as recorded in 1989 was approximately 5800 Mℓ. Approximately 85% of this water was discharged as effluent (4872 Mℓ/year) containing high organic loads and suspended matter. The COD ranged from 2380 to 8942 mg/ℓ (7140-26 826 mg C/ℓ) and the TKN was between 0.71 and 24 mg/ℓ (0.71-24 mg N/ℓ) (DWA, 2001). The number of abattoirs has increased to approximately 479 in 2014 (Neethling, 2014). By using a linear correlation, the effluent was estimated to be 8188 Mℓ/year for 2014. Table 33 gives the estimated volume, concentration and complexity of the red meat abattoir wastewater (see also Appendix C.4.4). In addition to its organic complexity, this wastewater is contaminated by antibiotics and growth hormones, as well as pesticides to control external parasites. These compounds were administered to animals during their lifetime (IWA, 2009).

Table 33: Volume, concentration and complexity data for the South African red meat abattoir industry (summarised from Appendix C.4.4)

Effluent volume in South Africa	**Total estimated effluent volume in South Africa**	*Mℓ/year*	8188 (estimate by extrapolation)
	Days of operation	*days*	365
	Total estimated effluent volume in South Africa	*Mℓ/day*	22.4
Cross-reference	**To worksheet with primary data and calculations**		Appendix C.4.4
Distribution: number of plants	**TOTAL**		**480** (estimate)
	Micro	*<0.5 Mℓ/day*	
	Small	*0.5-2 Mℓ/day*	
	Medium	*2-10 Mℓ/day*	
	Large	*10-25 Mℓ/day*	
	Macro	*>25 Mℓ/day*	
Concentration	**Estimated average carbon content**	*mg/ℓ*	16 983
	Estimated average nitrogen content	*mg/ℓ*	12.36
	Estimated average phosphorus content	*mg/ℓ*	
	pH		5.7-8.4
	Conductivity	*mS/m*	
Complexities	**Solids component**		Fat, viscera, blood, skin, hair, flesh, faeces, manure, grit and undigested feed
	Toxic compounds		Antibiotics, growth hormones, pesticides
	Metals		
	Complex organics		Fats, oils and protein
	Other valuable components		Skin for leather products

Dairy industry

The South African dairy industry produced approximately 230 million litres of milk during February 2016 (MPO, 2016). Milk production is seasonal, with the lowest milk yields from April to July and 30% to 40% more from September to November. To reduce seasonality, dairy processors encourage farmers to produce more milk between April and July by paying highest prices during these months. Cows average about 19ℓ milk per day per cow throughout the year (Lassen, 2012).

Primary dairy industry: milking parlours

A study by Du Preez (2010) on the treatment of typical South African milking parlour wastewater (i.e. primary diary industry) by means of anaerobic sequencing batch reactor technology estimated the water usage in five typical South African milking parlours. For these, an annual wastewater production ranged from 15 to 51 $\ell \cdot cow^{-1} \cdot day^{-1}$ (average 33 $\ell \cdot cow^{-1} \cdot day^{-1}$). The water used for the cleaning-in-place washing of the milking equipment was similar in all five milking parlours and ranged from 4.9 to 6.4 $\ell \cdot cow^{-1} \cdot day^{-1}$.

Depending on the literature, there are either approximately 4000 milk producers in South Africa (Brand South Africa, 2008) or between 2200 and 2700 milk producers (DAFF, 2013; Erasmus, 2012; GCIS, 2013). The Dairy Industry Review of 2014 (SAMPRO, 2014) reports that 2638 Mℓ milk was produced in 2010; it increased to 2817 Mℓ in 2013. Working on the assumption that there are 2500 milk producers in South Africa, and that each milk producer has an average of 151 cows (Du Preez, 2010), and the average milk production is 19 ℓ/cow, then this equates to 2618 Mℓ milk that was produced annually in 2010 (assuming 365 days of operation), and an average of 1.74 ℓ wastewater per litre milk produced. This then equates to an average of 4547 Mℓ/year of wastewater produced. Information regarding the water usage and effluent production from the five milking parlours in the Free State and the Western is summarised in Appendix C.4.5.

Information from Burton et al. (2009) suggested an average of 5.3 g COD/ℓ (15 900 mg C/ℓ). Du Preez (2010) reported 20 g-COD/ℓ (60 000 mg C/ℓ) (unfiltered) and 10 g/ℓ COD (30 000 mg C/ℓ) (filtered), 350 mg N/ℓ TN and 40 mg P/ℓ TN. Using an average of 15 000 mg/ℓ COD (45 000 mg C/ℓ), Table 34 summarises the volume, concentration and complexity for the South African primary dairy industry.

Table 34: Volume, concentration and complexity data for the South African primary dairy industry (summarised from Appendix C.4.5)

Effluent volume in South Africa	**Total estimated effluent volume in South Africa**	*Mℓ/year*	4547
	Days of operation	*days*	365
	Total estimated effluent volume in South Africa	*Mℓ/day*	237
Cross-reference	**To worksheet with primary data and calculations**		Appendix C.4.5
Distribution: number of plants	**TOTAL**		**2500** (estimated)
	Micro	*<0.5 Mℓ/day*	
	Small	*0.5-2 Mℓ/day*	
	Medium	*2-10 Mℓ/day*	
	Large	*10-25 Mℓ/day*	
	Macro	*>25 Mℓ/day*	
Concentration	**Estimated average carbon content**	*mg/ℓ*	45 000
	Estimated average nitrogen content	*mg/ℓ*	350
	Estimated average phosphorus content	*mg/ℓ*	40
	Ph		8.2
	Conductivity	*mS/m*	
Complexities	**Solids component**		Faeces, grit
	Toxic compounds		
	Metals		
	Complex organics		Fats, proteins
	Other valuable components		

Secondary dairy industry: milk processing

Apart from the primary dairy (milking) industry, the secondary dairy industry processes all milk to produce products such as long-life milk, cheese, butter, yogurt, milk powder, whey powder and condensed milk. Water use and the effluent discharged vary with the type of produce and size of the company (Steffen, Robertson and Kirsten Inc, 1989a). This NatSurv 4 report estimates that the dairy processing industry in 1986 used approximately 4.5 million m^3 water. In 1986, there were more than 150 factories producing a wide range of products such as fresh milk, butter, cheese, yogurt, milk powder, ice cream, condensed milk and various milk-based desserts (Steffen, Robertson and Kirsten Inc, 1989a). In 2012, there were 131 companies in South Africa processing raw milk they produced themselves to secondary products such as pasteurised milk, yogurt and cheese. In the same year, there were 163 companies that bought raw milk and processed it to products such as pasteurised milk, yogurt, sour milk, buttermilk, milk powder, buttermilk powder, whey powder and cheese (World Dairy Summit, 2012). These factories discharged large quantities of effluent from the processing and cleaning processes, the ratio being dependent on the particular products made. In the case of pasteurised milk, the effluent discharge was often 85% to 90% of water intake, for butter and cheese 90% to 95%, whereas for milk powder and condensed milk sometimes more than 100% (Steffen, Robertson and Kirsten Inc, 1989a; Strydom, et al., 1997). The revised NatSurv report on dairies has not been published and should available later in 2016. A preliminary table of the volume, concentration and complexity data for the South African secondary dairy industry is shown in Appendix C.4.5.

Fishery industry

Information on the South African fisheries wastewater was difficult to source and there is no NatSurv report. There are more than 100 processing factories in South Africa according to the Status of the South African Marine Fishery Resources report for 2014 (DAFF, 2014).

The information used in this section was collected from Brazil (Quiroz, et al., 2013) and Canada (Chowdhury, et al., 2010).The wastewater that originates from fish processing units depends on the composition of the raw fish or shellfish, the unit processes used, the quality of the processing water and additives such as brine and oil used for canning processes (Chowdhury, et al., 2010). Generally, 11 m^3 water is consumed per tonne fish processed (11 ℓ/kg), resulting in a significant volume of wastewater (Quiroz, et al., 2013). For a large salmon processing plant in Canada, the wastewater discharge is 3.12 ℓ/kg and for small salmon plants 9.90 ℓ/kg, while for the canning of tuna and sardines it is between 14 ℓ/kg and 22 ℓ/kg (Chowdhury, et al., 2010). In South Africa, the hake catch is approximately 145 000 tonnes per year and is included in the total catch (including other species such as monk, kingklip and horse mackerel) of approximately 160 000 tonnes per year (SADISTA, 2013). Using these data for the South African catch and the wastewater estimation of 11 ℓ/kg, the annual wastewater generated can be estimated as 1760 Mℓ/year (Table 35).

Table 35: Volume, concentration and complexity data for the South African fishery industry

Effluent volume in South Africa	**Total estimated effluent volume in South Africa**	*Mℓ/year*	1 760
	Days of operation	*days*	365
	Total estimated effluent volume in South Africa	*Mℓ/day*	4.8
Distribution: number of plants	**TOTAL**		**100 (estimated)**
	Micro	*<0.5 Mℓ/day*	
	Small	*0.5-2 Mℓ/day*	
	Medium	*2-10 Mℓ/day*	
	Large	*10-25 Mℓ/day*	
	Macro	*>25 Mℓ/day*	
Concentration	**Estimated average carbon content**	*mg/ℓ*	17 400 (4 859-30 000)
	Estimated average nitrogen content	*mg/ℓ*	35.2 (7-69)
	Estimated average phosphorus content	*mg/ℓ*	–
	Ph		6.4-10
	Conductivity	*mS/m*	–
Complexities	**Solids component**		Scales, flesh, blood, bones
	Toxic compounds		–
	Metals		–
	Complex organics		Oils, protein FOG: 60-800 mg/ℓ
	Other valuable components		

Fish processing wastewater contains high soluble, colloidal and particulate organic content (TSS range from 200-10 000 mg/ℓ), with COD concentrations ranging from 3000-10 000 mg/ℓ (9000-30 000 mg C/ℓ) for herring processing or even as low as 1600 mg/ℓ (4800 mg C/ℓ) for tuna processing (Chowdhury, et al., 2010). The ammonia concentration ranged from 0.7 to 69.7 mg/ℓ for a few fish processing plants with 42 mg/ℓ for salmon processing and 20 mg/ℓ for groundfish processing. For fish condensate, the ammonia concentration can be as high as 2000 mg/ℓ (Chowdhury, et al., 2010). Phosphorous partially originates from the fish during processing but can also be introduced with cleaning agents (Chowdhury, et al., 2010). The pH value ranges from 6.4 to 10.

FOGs are also important parameters of fish processing wastewater, approximately 60% of the oil and grease originates from the butchering process while the remaining 40% is from the fish canning and fish processing operations (Chowdhury, et al., 2010). Approximate FOG concentrations are between 60 mg/ℓ and 800 mg/ℓ.

4.3.4 Plant-based food industry

Putting together the industrial categories used in several sources (Burton, et al., 2009; Cloete, et al., 2010; WRC, 2016a) this sub-sector includes a considerable number of industries. These can be subdivided into the following rough groupings:

- (i) *Raw plant food handling* consists of fruit, vegetables and grains with possible freezing, milling and packing.
- (ii) *Processed plant food* encompasses canning (and bottling and tetra paks), sugar, yeast and edible oils.
- (iii) *Cooked plant food* comprises bakery, confectionery and snack production.
- (iv) *Alcoholic beverages* include brewing, wine making and distilling.
- (v) *Soft drinks* incorporate sodas (fizzy drinks), fruit juices and concentrates.

Processing raw plant food requires large volumes of potable water. The wastewater generated in food operations is non-toxic but has a high BOD, suspended solids in the form of sugars, hemicellulose, cellulose, lignin and surfactants (used in washing the produce). Processed plant-based food wastewater can also contain amounts of salt, flavouring, colouring material, acid, alkali and oil or fat (IWA, 2009).

Cloete et al. (2010) identified soft drinks, brewing and sugar as the three highest wastewater producers in the plant-based food sub-sector. These and the edible oil industry are considered here. This is followed by a section commenting on several other industries in this sub-sector. Details are included in the data in Appendix C.4.

Soft drink industry

South Africa produced approximately 3700 Mℓ of soft drinks in 2012 (Pollution Research Group, 2015). The effluent generated from the soft drink industry contains wasted soft drink and syrup, wash water from bottle and crate washing, caustic soda (NaOH), detergent and machine lubricant. For NatSurv 3 Edition 2 (Pollution Research Group, 2015), 67 production sites were identified in the soft drink industry. All of these were approached; however, data was only obtained from 16 of these. These 16 companies ranged in annual production volume from three at <5 Mℓ, thorough six at between 10 Mℓ to 100 Mℓ, 6 at between 100 Mℓ and 340 Mℓ, to one producing >500 Mℓ per annum.

The amount of wastewater generated at the production sites varies enormously, depending not only on the annual production volume, but also on whether it produces carbonated drinks, bottled water or fruit juices, and which parts of the entire process are included on-site. The average specific water intake is 1.6 ℓ/ℓ for carbonate drinks, 1.4 ℓ/ℓ for bottled water and 2.2 ℓ/ℓ for fruit drinks. The reported SEV has an extremely wide range even within each subgroup of factories (Pollution Research Group, 2015) (Appendix C.4.6). An average SEV for these soft drinks can be calculated as 1.1 ℓ/ℓ. Using the amount of soft drinks produced (3 700 Mℓ), the equivalent effluent is approximately 4 070 Mℓ/year (Table 36).

Wastewater is generally high in COD and TDS, and contains nitrates, phosphates, sodium and potassium. An average COD was calculated from the extremely varied values for COD that were given in NatSurv 3 (Pollution Research Group, 2015) (see also Appendix C.4.6); this COD value is 6087 mg/ℓ (18 262 mg C/ℓ). The total carbon that can be recovered nationally from soft drink effluent streams would then be approximately 74 326 t/year. The TDS also appears to vary considerably even within the two categories of carbonated and fruit juice drinks. The pH fluctuates widely with different stages of the process; for carbonated drinks it can vary between 2.8 and 12.2, and for fruit drinks between 6.1 and 11. The higher pH values result from cleaning with caustic soda (NaOH) (Pollution Research Group, 2015). The values of nitrogen and phosphates were not measured in the survey.

Table 36: Volume, concentration and complexity data for the South African soft drink industry (summarised from Appendix C.4.6)

Effluent volume in South Africa	**Total estimated effluent volume in South Africa**	*Mℓ/year*	4070
	Days of operation	*days*	365
	Total estimated effluent volume in South Africa	*Mℓ/day*	11.2
Cross-reference	**To worksheet with primary data and calculations**		Appendix C.4.6
Distribution: number of plants	**Total**		**67**
	Micro	*<0.5 Mℓ/day*	
	Small	*0.5-2 Mℓ/day*	
	Medium	*2-10 Mℓ/day*	
	Large	*10-25 Mℓ/day*	
	Macro	*>25 Mℓ/day*	
Concentration	**Estimated average carbon content**	*mg/ℓ*	18 262
	Estimated average nitrogen content	*mg/ℓ*	
	Estimated average phosphorus content	*mg/ℓ*	
	Ph		2.8-12.2
	Conductivity	*mS/m*	
Complexities	**Solids component**		In fruit juice effluent
	Toxic compounds		
	Metals		
	Complex organics		
	Other valuable components		

Alcoholic beverage industry

In South Africa, a total of 3946 Mℓ of alcoholic beverages were produced in the year from July 2014 to June 2015; with the market share by volume of beer 77.7% compared to spirits 2.8%, ready to drink alcoholic beverages 10.6%, wine 8.2%, and fortified wine 0.7% (Holtzkampf, 2016). The amount of wastewater produced depends on the production process, with details on breweries, wineries and distilleries given below.

Breweries

From the NatSurv 1 report (Binnie and Partners, 1987b), an average of 89.8 Mℓ/month of beer was produced, i.e. 1077.6 Mℓ/year. An annual brewery effluent volume in South Africa of 5.9 million m^3/year (5900 Mℓ/year) was generated, which relates to an SEV of 5.5 ℓ/ℓ. Burton et al. (2009) reported that 2604.6 Mℓ/year beer was produced in 2008 and 8334 Mℓ/year wastewater generated with an SEV of approximately 3.2 ℓ effluent/ℓ beer produced at the brewery considered. Typical SEV for breweries is between 3 ℓ/ℓ and 5 ℓ/ℓ beer according to information from the IWA WaterWiki (IWA, 2009). The typical composition of untreated wastewater effluents can be seen in Appendix C.4.7.

The effluents from the individual steps of the brewery process vary with effluents from the fermentation and filtering processes containing high COD and BOD but low volume (about 3% of the total wastewater volume). Bottle-washing produces large volumes of effluent with low organic content. The COD values between the different breweries ranged between 700 mg/ℓ and 20 000 mg/ℓ. The TDS ranged between 5600 mg/ℓ and 9900 mg/ℓ (Binnie and Partners, 1987b). Typical COD, nitrogen and phosphorous concentrations for brewery wastewaters are 2000-6000 mg/ℓ (6000–18 000 mg C/ℓ), 25-80 mg/ℓ and 10-50 mg/ℓ respectively (Brito, et al., 2007). The total brewery effluent has an average pH of 7, but the pH value fluctuates from 4.5 to 12 depending on the cleaning process (Brito, et al., 2007).

Table 37: Volume, concentration and complexity data for the South African brewing industry (summarised from Appendix C.4.7)

Effluent volume in South Africa	**Total estimated effluent volume in South Africa**	*Mℓ/year*	8 334
	Days of operation	*days*	365
	Total estimated effluent volume in South Africa	*Mℓ/day*	22.8
Cross-reference	**To worksheet with primary data and calculations**		Appendix C.4.7
Distribution: number of plants	**Total**		**7**
	Micro	*<0.5 Mℓ/day*	–
	Small	*0.5-2 Mℓ/day*	–
	Medium	*2-10 Mℓ/day*	–
	Large	*10-25 Mℓ/day*	–
	Macro	*>25 Mℓ/day*	–
Concentration	**Estimated average carbon content (range)**	*mg/ℓ*	12 000
	Estimated average nitrogen content (range)	*mg/ℓ*	52.5
	Estimated average phosphorus content	*mg/ℓ*	30
	Ph		7
	Conductivity	*mS/m*	
Complexities	**Solids component**		
	Toxic compounds		
	Metals		
	Complex organics		
	Other valuable components		

Wineries

The SAWIS report (2016) states that the annual production of wine in 2015 was 968.4 Mℓ, while another source noted 959 Mℓ/year for 2015 (Froud, 2016). Each litre of wine generates between 1 ℓ and 4 ℓ of winery wastewater, which is regarded as the most significant environmental risk from wine cellars (Welz, et al., 2015). If an average SEV of 2.5 ℓ/ℓ is used for 968.4 Mℓ wine produced, then the effluent generated was 2421 Mℓ. Effluent COD values typically range from 800 mg/ℓ to 12 800 mg/ℓ, but peaks greater than 25 000 mg/ℓ have been reported (Malandra, et al., 2003; Saadi, et al., 2007). Inorganics, including sodium and potassium, are often found in high concentrations (Welz et al., 2015). The TKN is approximately 110 mg/ℓ and the total orthophosphates is 52 mg/ℓ (Cai, et al., 2013). The winery effluent consists of varying ratios of readily biodegradable sugars, moderately biodegradable alcohols and slowly biodegradable recalcitrant phenolics (Welz et al., 2015). The phenol concentration in some effluents can range from 29 mg/ℓ to 474 mg/ℓ and, due to its antimicrobial activity, is responsible for the strong inhibitory effects on microbial activity in WWTW, hence should be removed (Melamane, et al., 2007). The pH value ranged from 4.0 to 5.7 (Brito et al., 2007) (see also Appendix C.4.7).

Distilleries

Melamane et al. (2007) presented a review on the wastewaters created in the distillery industry with the emphasis on using anaerobic membrane reactors to remediate it. Appendix C.4.7 summarises the chemical characteristics of distillery wastewaters (Melamane et al., 2007). Distilleries can be divided into two groups, namely, for human consumption and fuel ethanol production.

Sugar industry

The sugar industry is a major example of a processed plant-based food industry in South Africa, which supports the livelihood of approximately 1 million South Africans. Some 2.3 million tonnes of sugar were produced in the 2014/2015 season (SASA, 2016). An average specific water intake of 0.6 m^3/t (0.0006 Mℓ/t) sugarcane is used (Steffen, Robertson and Kirsten Inc., 1990). Typically, 18 m^3 wastewater is generated per 100 t (0.00018 Mℓ/t) of sugar cane processed, or 0.75 to 1.5 Mℓ/day wastewater (roughly 30% of the water requirement). Sugarcane is processed continuously from April to December. Plant maintenance occurs over the remainder of the year (Steffen, Robertson and Kirsten Inc., 1990). The annual wastewater generated per season (nine months or 274 days) was calculated to be 411 Mℓ/year. The organic content in the wastewater is high with a COD from 1500 to 2000 mg/ℓ; however, the wastewater nitrogen- and phosphorous deficient (Steffen, Robertson and Kirsten Inc., 1990). Using this data, the average estimated carbon that can be recovered from wastewater is calculated to be 2156 t/year (Table 38). The major liquid by-product of a sugar processing plant is molasses; this can be fermented to produce fuel ethanol or sold to bioprocessing and animal feed industries as a nutrient source. The wastewater from the ethanol fermentation is called vinasse. For every litre of ethanol produced, 10 ℓ to 15 ℓ of vinasse is generated (Christofoletti et al., 2013).

Table 38: Volume, concentration and complexity data for the South African sugar industry

Effluent volume in South Africa	**Total estimated effluent volume in South Africa**	*Mℓ/year*	411
	Days of operation	*days*	274
	Total estimated effluent volume in South Africa	*Mℓ/day*	1.5
Cross-reference	**To worksheet with primary data and calculations**		
Distribution: number of plants	**Total**		**14**
	Micro	*<0.5 Mℓ/day*	
	Small	*0.5-2 Mℓ/day*	
	Medium	*2-10 Mℓ/day*	
	Large	*10-25 Mℓ/day*	
	Macro	*>25 Mℓ/day*	
Concentration	**Estimated average carbon content**	*mg/ℓ*	5 250
	Estimated average nitrogen content	*mg/ℓ*	
	Estimated average phosphorus content	*mg/ℓ*	
	Ph		
	Conductivity	*mS/m*	
Complexities	**Solids component**		
	Toxic compounds		
	Metals		
	Complex organics		
	Other valuable components		

Edible oil industry

In 1989, there were 16 edible oil plants in South Africa. The NatSurv 6 (Steffen, Robertson and Kirsten Inc., 1989b) report represents data obtained from 11 of these plants. It was estimated that the edible oil industry consumed approximately 1.75 million m^3 water/year (1 700 million Mℓ/year). An oil plant typically discharges about 35% of the incoming water to sewers (Steffen, Robertson and Kirsten Inc., 1989b). The total quantity of edible oil produced in 1989 was 250 000 t (0.25 Mt/year), which was expected to increase by 3% per annum. Using the principle of compound interest, the total quantity of edible oil was estimated to be 0.56 Mt/year in 2016 (Steffen, Robertson and Kirsten Inc., 1989b).

The water used and wastewater generated for 2016 were calculated from the 1989 data using the same ratios (Appendix C.4.8), i.e. no improved efficiencies were considered although these would be expected to have occurred. The water used and wastewater generated for 2016 were thus estimated as 3776 Mℓ/year and 1361 Mℓ/year respectively. A study by Roux–Van der Merwe, et al. (2005) on fungal treatment of edible oil containing industrial effluent found COD to range between 16 000 mg/ℓ and 250 000 mg/ℓ (48 000-750 000 mg C/ℓ), the conductivity between 88.2/m and 268/m, and the TKN between 16.1 mg/ℓ and 45.9 mg/ℓ. No quantitative information was given on phosphate other than its content being significant (Roux–Van der Merwe, et al., 2005; Steffen, Robertson and Kirsten Inc., 1989b). Surujlal et al. (2004) reported average phosphate data ranging from 500 mg/ℓ to 4510 mg/ℓ (163.2-1471.6 mg P/ℓ) (see Appendix C.4.8). Replacing phosphoric acid with citric acid in the process reduced the TP concentration of the effluent to meet discharge standards (Surujlal, et al., 2004). The revised NatSurv report on edible oils with updated data will be available in 2017.

Table 39: Volume, concentration and complexity data for the South African edible oil industry (summarised from Appendix C.4.8)

Effluent volume in South Africa	**Total estimated effluent volume in South Africa**	*Mℓ/year*	1361 (estimate)
	Days of operation	*days*	365
	Total estimated effluent volume in South Africa	*Mℓ/day*	3.73
Cross-reference	**To worksheet with primary data and calculations**		Appendix C.4.8
Distribution: number of plants	**Total**		
	Micro	*<0.5 Mℓ/day*	
	Small	*0.5-2 Mℓ/day*	
	Medium	*2-10 Mℓ/day*	
	Large	*10-25 Mℓ/day*	
	Macro	*>25 Mℓ/day*	
Concentration	**Estimated average carbon content**	*mg/ℓ*	399 000
	Estimated average nitrogen content	*mg/ℓ*	31
	Estimated average phosphorus content	*mg/ℓ*	2505
	Ph		4.6-10.6
	Conductivity	*mS/m*	98-388
Complexities	**Solids component**		
	Toxic compounds		
	Metals		
	Complex organics		
	Other valuable components		

Other plant-based food industries

Canning industry

The canning of fruit and vegetables is done to preserve perishable foods so that they can be stored for prolonged periods of time. A study by Binnie and Partners (1987a) investigated the process of canning certain fruits (apples, apricots, guava and peaches) and vegetables (beans in tomato, beetroot, corn and green beans). The raw materials processed, water intake, effluent produced, COD and TSS values of these are summarised in Table C-31 in Appendix C. The total amount of effluent produced was 1074 Mℓ/year to can 0.2 million tonnes of raw material. The COD values ranged from 700 mg/ℓ to 6500 mg/ℓ (2100–19 500 mg C/ℓ) and the TSS from 195-400 mg/ℓ. No values for nitrogen and phosphorous content were given and only a pH range of 4.4 to 11.7 for peach canning was given. Since the 1970s, the industrial practices and optimisation of these have changed, yet no comprehensive evaluation has been performed since 1987 according to the review of Khan et al. (2015) of the fruit waste streams of South Africa (Appendix C.4.9).

Fruit processing industry

Several studies have investigated the valorization of food processing wastewater by producing methane through anaerobic digestion. Some examples are given in Appendix C.4.9.

The study by Khan et al. (2015) reviewed the fruit waste streams of South Africa in terms of the solid waste and wastewater produced. Fruit processing in South African includes canning, juicing, winemaking and fruit drying. The water consumption that occurs during these processes is reported as between 7 m^3/t and 10.7 m^3/t (0.007-0.0107 Mℓ/t) of raw produce. The wastewaters generally contain particulate organics, suspended solids, various cleaning solutions and softening or surface-additives (Khan, et al., 2015). The focus in this report was on olive oil processing, citrus, grapes and apples.

Confectionery industry

South Africa is said to have one of the largest and most well-established confectionery markets on the African continent with consumption of 1.3 kg of chocolate per capita per year and 2.1 kg of sugar confectionery per year, as recorded in 2010 (Food Stuff South Africa, 2011). The confectionery industry is divided into three segments, namely, chocolate, flour (starch) and sugar confectionery. Chocolate confectionery comprises mainly chocolate bars, chocolate blocks, boxed chocolates and other chocolate products. Flour confectionery includes items made from the flour or starch, mainly as bakery products. Sugar confectionery includes the remainder of products in the confectionery industry. Sugar-free confectionery contains no sugar or sugar alternatives (Ersahin, et al., 2011).

The confectionery industry can generate large amounts of wastewater containing high concentrations of readily biodegradable organic materials characterised with high COD and BOD (Beal & Raman, 2000; Diwani, et al., 2000; Ersahin, et al., 2011). The range of COD reported in confectionery wastewater is between 2840 mg/ℓ and 19 900 mg/ℓ COD and 1840 mg/ℓ and 4910 mg/ℓ BOD (Ersahin, et al., 2011) (see also Appendix C.4.10).

4.3.5 Other organics-based industries

From industrial categories used in several sources (Burton, et al., 2009; Cloete, et al., 2010; WRC, 2016a), the remaining industrial sectors can be subdivided into organic and inorganic sectors. This report on WWBRs focuses on the organic sub-sector. These organic wastewaters include those from the cleaning and cosmetics, dyeing and colouring, laundry, pharmaceutical, paint, plastic, tanning and leather, and textiles industries.

Cloete et al. (2010) recorded the textile industry as the highest wastewater producer of these sectors, although it is noted that this data was from before the production volume of the South African textile industry reduced. The wastewater from these industries varies from site to site and contains unusual components specific to the manufacturing processes. It may contain reactive or hazardous components, like unreacted catalyst, extreme pH, salt concentration, heavy metals, or toxic solvents used in chemical synthesis. The complexity will vary from simple, predictable, consistent streams to highly varied streams of undisclosed composition. As the company producing the stream has the most information about the wastewater, the most experience with the components in the wastewater and may be unwilling to share the information due to proprietary concerns, substantive chemical production wastewater treatment and beneficiation are best considered as a point-source solution, and not mixed with other streams before beneficiation. Two example industries, textiles and cleaning agents manufacture, have been considered in Appendix C.4.11 and Appendix C.4.12.

4.4 Potential of South African Wastewaters as Feedstocks for Wastewater Biorefineries

In this section, the potential of generating value-added products from wastewater in an industry-tailored fashion has been illustrated. This is not intended to provide a comprehensive inventory but rather as a starting point for conceptualising WWBRs in South Africa and defining future research. Challenges associated with compiling a comprehensive inventory of South African wastewaters include the lack of up-to-date information, data available having been generated from small sample sizes owing to a limited number of industries being willing to disclose these numbers, and discrepancies in data collected from the same industry. Hence, a rudimentary inventory of a number of important contributing industries to South Africa's wastewaters has been compiled in this chapter. This provides a basis on which to investigate the potential of wastewater as a source of valuable nutrients for the production of biobased products, as a source of clean water and as a source of revenue with the aiming of facilitating its implementation in the near future.

The products from wastewaters, however, do not typically find favour for use in the food and beverage industry itself, due to health (and religious) concerns. However, there is potential for products used downstream of the food and beverage production, e.g. in wastewater treatment as bioflocculants. Thus, for example, polylactic acid produced from an organic waste stream could not be recommended for use as food packaging, but could be used for paper coating for advertising billboards or plastic wrapping of sealed beverage containers. In valorizing these industrial wastewaters, a partnership between the industry generating the waste stream, the biorefinery and the industry using the product is desired, preferably in close physical proximity.

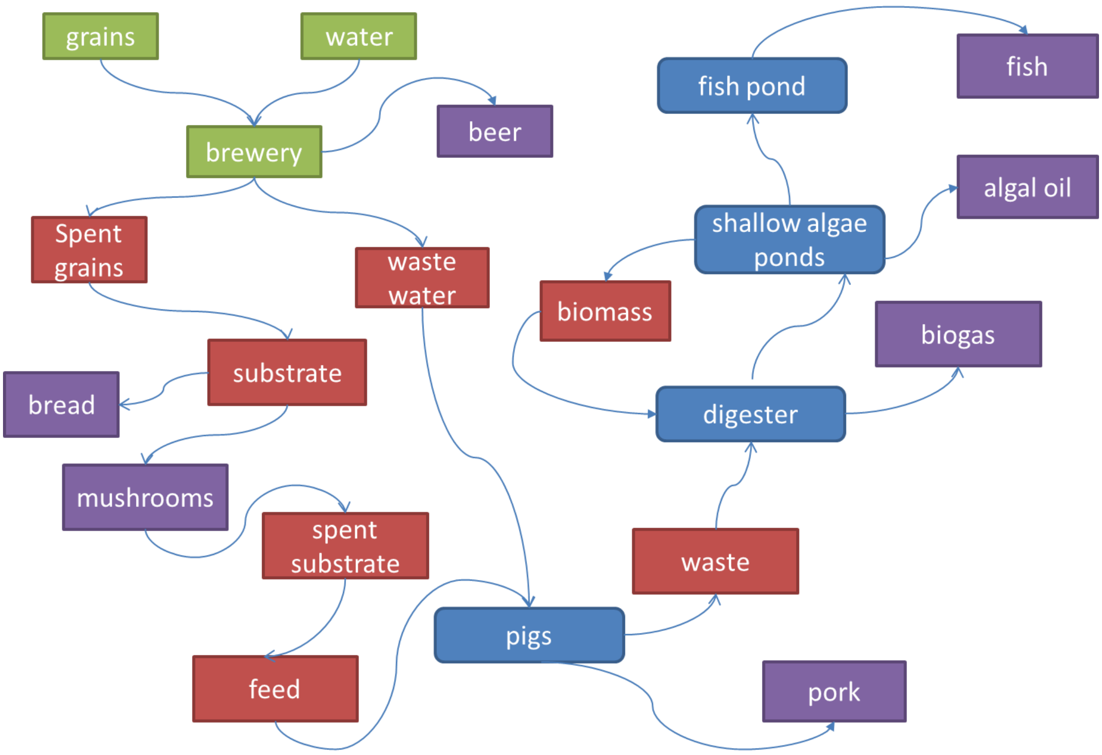


Figure 9: Brewery process flow diagram (adapted from (ZERI, n.d.))

The brewing industry has been recognised as favourable to WWBRs as these wastewaters tend to be readily biodegradable, do not contain biohazardous material like heavy metals, and may contain microbial consortia already adapted to their environment. Thus, in principle, these wastewaters would be well suited to bioconversion.

Two examples of using brewery waste have been reported as part of the ZERI brewery process (ZERI, n.d.). In the first example, the spent grain from the brewery process was used to grow mushrooms. The spent substrate from mushroom production was then used as animal feed (Figure 9) (Zhang, et al., 2007). In the second example, bioflocculant produced from brewery wastewater was used to treat indigotin printing and dyeing wastewater with a maximum removal of the COD and the chroma of 79.2% and 86.5%, respectively (Zhang, et al., 2007).

5 REVIEW OF POTENTIAL BACTERIAL PRODUCTS IN THE SOUTH AFRICAN CONTEXT

The key to the concept of the WWBR is producing multiple value-added products simultaneously while improving water quality. Depending on the composition of the feed stream to the WWBR, the process train used may have different groups of products associated with them. As has already been noted (Section 3.3.2), not all bioproducts are suitable for production in WWBRs due to the unique constraints presented by wastewater streams, especially dilute streams, and the environment in which they typically occur. This means that potential products must be carefully assessed and a selection made from the most viable alternatives.

Various options for biobased products microbially produced using predominantly the organic, carbon-rich components of the wastewater are assessed here. A broad overview of biobased products is given in Section 5.1. Following this, biopolymers (Section 5.2) and biobased building blocks (Section 5.3) are reviewed as potential products, with a final focus on two biopolymers, the biodegradable bioplastic PHA (Section 5.4.1) and the water-retaining PGA (Section 5.4.2). Finally (Section 5.5), product-related factors are considered specifically in the context of integrating units into a WWBR.

5.1 Biobased Products

A European Commission-sponsored study on promoting the implementation of biobased products (European Commission, 2009) described biobased products as non-food crops that can be derived from biomass (plants, algae, crops, trees, marine organisms, and biological waste from households, animals and food production). These products ranged from high-value added chemicals such as pharmaceuticals or food additives to high-volume products such as biopolymers or chemical feedstocks (European Commission, 2009). Table 40 presents an overview of common biobased products and their corresponding characteristics.

Table 40: An overview of common biobased products and their corresponding characteristics (excluding food, energy and fuel products) (European Commission, 2009)

Product type	Characteristics or functionalities
Chemical and chemical building blocks Various chemicals made from renewable raw materials.	Sustainable chemical production, lower GHG and other emissions in production, lower resource use in terms of energy and water with less waste depending on production process, typically better biodegradability, potentially less toxic.
Biobased plastics, biopolymers and biomaterials e.g. PHA, polyethylene (PE), polylactic acid (PLA) and propanediol-based plastics from biotransformation of glucose, sucrose, plant-derived carbohydrates or starch.	Sometimes biodegradable and/or compostable, lower GHG emissions, potentially less toxic, materials with new qualities (composite materials, textiles, boards etc).
Renewable construction materials and composite materials from natural fibres e.g. flax, hemp, jute, wood used in building construction and automotive components etc.	Good mechanical properties (impact resistance, acoustic qualities, strongly reduced weight/lightweight concrete), better waste recycling (easier to recycle or burn than fibreglass).
Surfactants Surfactants lower surface tension of liquids and are used in soaps, detergents, pharmaceuticals, food additives, etc. and for the production of emulsions and foams. Chemical surfactants are produced largely from oils. Next generation biosurfactants can be produced using algae, fungi or bacteria.	Low eco-toxicity, offers biodegradability and compostability. Enzyme-based detergents are used in household washing machines and offer environmental advantages (lower temperature, energy savings, more efficient washing, have replaced phosphorus).
Biosolvents Solvents are used in paints, inks, varnishes, adhesives etc.	Biobased solvents do not emit VOCs that are harmful to human health and the ozone layer. Some 23% of VOCs emitted into the air are from petrochemical solvents.
Biolubricants Lubricants made from vegetable oils and their direct derivatives for engines, gearboxes, chains, etc.	Biodegradable, lower toxicity, can be used in sensitive environments, may reduce pollution from non-biodegradable or otherwise environmentally unacceptable lubricants from machines and vehicles.
Enzymes, amino acids and organic acids These types of molecules can be used e.g. to enhance industrial processes to produce food and feed supplements and as building blocks for biopolymers, cosmetics and pharmaceuticals.	Economic value-added when used as inputs in various industries. Constitute technological advances that improve products or processes. Environmental benefits, e.g. enzymes can replace several steps in chemical synthesis, save energy and avoid toxic chemicals (e.g. acid, alkali).

Biobased products may be classified into two groupings:

1. Biobased products that are chemically identical to their petrochemical counterparts (so-called 'drop-ins') can be used directly in the current industrial infrastructure. These can make an otherwise petroleum-based material partly or completely biobased.
2. Biobased chemicals and materials from renewable raw materials may provide products with unique characteristics that have not yet been produced from or are too costly to produce from petrochemical raw materials. These are termed novel biobased products. Table 41 presents a strength, weakness, opportunity and threat (SWOT) analysis on the two different kinds of bioproducts, according to Higson (2013).

Table 41: SWOT analysis of drop-in and novel bioproducts (Higson, 2013)

Strengths	Drop-in: known targets and downstream products Novel: exploit attributes of biomass or biological processing
Weaknesses	Drop-in: number of unit operations required Novel: requirement for product development
Opportunities	Drop-in: rapid route to market through existing infrastructure and know how Novel: provides new or improved functionality
Threats	Drop-in: challenge to achieve cost competitiveness Novel: immature supply chain and market awareness

Biobased products spread over a large spectrum of product types as shown in Table 40. However, owing to the large organic resource contained in wastewater, commodity products with a non-food use have been considered as the most relevant products of WWBRs. In this chapter, biopolymers form the focus as examples of relevant commodity products. An overview of biobased chemical building blocks is also presented as the basis for production of biopolymers.

5.2 Microbial Polymer Production

5.2.1 Biobased polymers

A polymer is a chemical compound made from repeating structural units (monomers) that can be synthesised in a polymerisation or fermentation process (Dammer, et al., 2013). Table 42 gives an overview of different biobased polymers and their production methods.

Biopolymers are naturally occurring polymers produced during the growth cycles of all microorganisms. They are usually synthesised by enzyme-catalysed reactions and chain-growth polymerisation reactions of activated monomers through complex metabolic cellular processes (Ghanbarzadeh & Almasi, 2013). Based on the different monomer units, biopolymers can be classified into three main groups (Kumar, et al., 2007; Mohanty, et al., 2005):

(i) Polynucleotides (RNA and DNA) consisting of 13 or more nucleotide monomers.
(ii) Polypeptides and proteins that are polymers of amino acids.
(iii) Polysaccharides, which are linear-bonded polymeric carbohydrate structures.

Table 42: Overview of different biobased polymers and their production methods (Weidmann-Marscheider, et al., 2005)

Biobased polymer (group)	Type of polymer	Structure/Production method
Starch polymers	Polysaccharides	Modified natural polymer
PLA	Polyester	Biobased monomer (lactic acid) by fermentation, followed by polymerisation
Other polyesters from biobased intermediates: i) Polytrimethylene terephthalate (ii) Polybutylene terephthalate (iii) Polybutylene succinate	Polyester	i) Biobased 1,3-propanediol by fermentation plus petrochemical terephthalic acid (or N,N-dimethyltryptamine (DMT)) ii) Biobased 1,4-butanediol by fermentation plus petrochemical terephthalic acid (or DMT) iii) Biobased succinic acid by fermentation plus petrochemical terephthalic acid (or DMT)
PHAs	Polyester	Direct production of polymer by fermentation or in a crop (wild type or genetically engineered bacteria; genetically engineered plants)

Biobased polymer (group)	Type of polymer	Structure/Production method
Polyurethanes	Polyurethanes	Biobased polyol by fermentation or chemical purification plus petrochemical isocyanate
Nylon: i) Nylon 6 ii) Nylon 66 (iii) Nylon 69	Polyamide	i) Biobased caprolactam by fermentation (ii) Biobased adipic acid by fermentation (iii) Biobased monomer obtained from a conventional chemical transformation from oleic acid via azelaic (di) acid
Cellulose polymers	Polysaccharides	(i) Modified natural polymer (ii) Bacterial cellulose by fermentation

5.2.2 What are bioplastics and how are they classified?

Plastic material is essentially a blend of one or more polymers and additives (Dammer, et al., 2013). (Haughn, 2015). The term “bioplastic” can be defined in a variety of ways, which can lead to ambiguity (Bio-Plastics, 2013):

- Biobased plastics: reference is made to the source of the raw materials.
- Biodegradable plastics: reference is made to their functionality and fate.
- Biocompatible plastics: reference is made to their functionality in terms of their compatibility with human or animal bodies.

The first two categories are usually used to classify a bioplastic, thus a bioplastic can be either biobased or biodegradable, or both. Biobased plastics are produced from biobased raw materials while biodegradable plastics can be produced from both biobased feedstock and petrochemical raw materials (Shen, et al., 2009). This can be represented in the material coordinate system given in Figure 10.

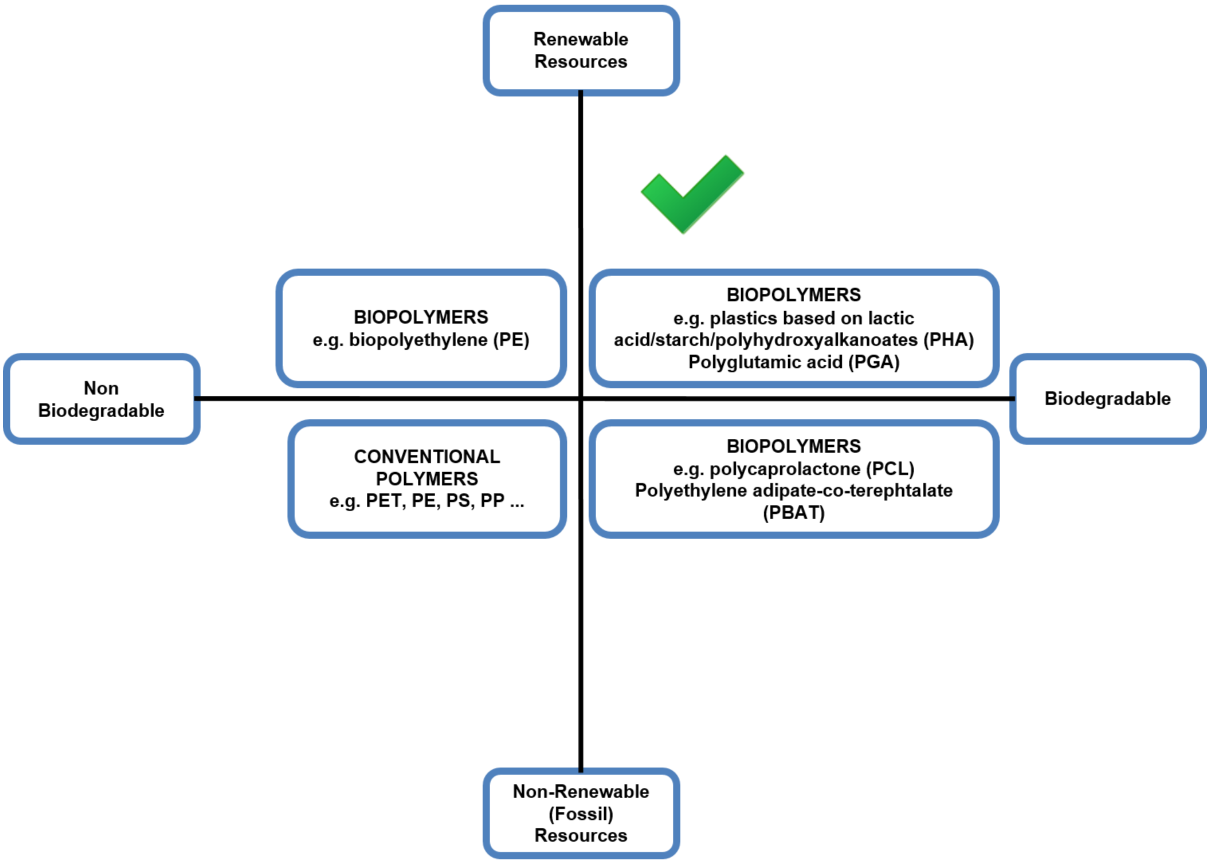


Figure 10: Material coordinate system for bioplastics (Scharathow, 2012)

The most attractive group in Figure 10 is the biobased and biodegradable bioplastics group, where the bioplastics can be fully degraded by microorganisms, thus having a closed carbon cycle (e.g. polylactides, aliphatic polyesters, polysaccharides and polyhydroxyalkanoate) (Reddy, et al., 2003).

Starch- and cellulose-based plastics are the most common biobased and biodegradable plastics and have been used for decades (Shen, et al., 2009).

PLA was discovered in 1932 but was only commercialised in the early 1990s owing to its similar properties to hydrocarbon polymers such as PET (Babu, et al., 2013). PLA is mainly used in food packaging applications but is not suitable for electronic devices and engineering applications (Babu, et al., 2013). PHAs are biologically synthesised polyesters that occur naturally in a variety of microorganisms. They were first discovered as bacterial storage products in the 1920s and commercialisation started in the 1990s (DiGregorio, 2009).

5.2.3 Bioplastics market trends

The current bioplastics market is growing strongly every year. The European Bioplastics is an association dedicated to help bioplastics industry in Europe achieve commercial success by providing unique networking possibilities with stakeholder groups (European Bioplastics, 2016).This association has conducted intensive market data research, some of which are publicly available and will presented in this section.

Bioplastics currently represent less than one percent of the 300 million tonnes of plastics produced globally (European Bioplastics, 2016). However, there are numerous driving factors promoting the growth of the bioplastics industry such as high consumer acceptance, climate change concerns, and depletion of fossil resources. The increasing rate of market penetration is also driven by the move of bioplastics from niche markets to mass markets with bioplastics being integrated into the packaging and automobile industries by existing companies such as Coca-Cola, Heinz, Mercedes and Toyota.

The latest market data published by European Bioplastics (2016) indicates that the production of bioplastics is expected to quadruple from around 1.7 million tonnes in 2014 to approximately 7.8 million tonnes in 2019.

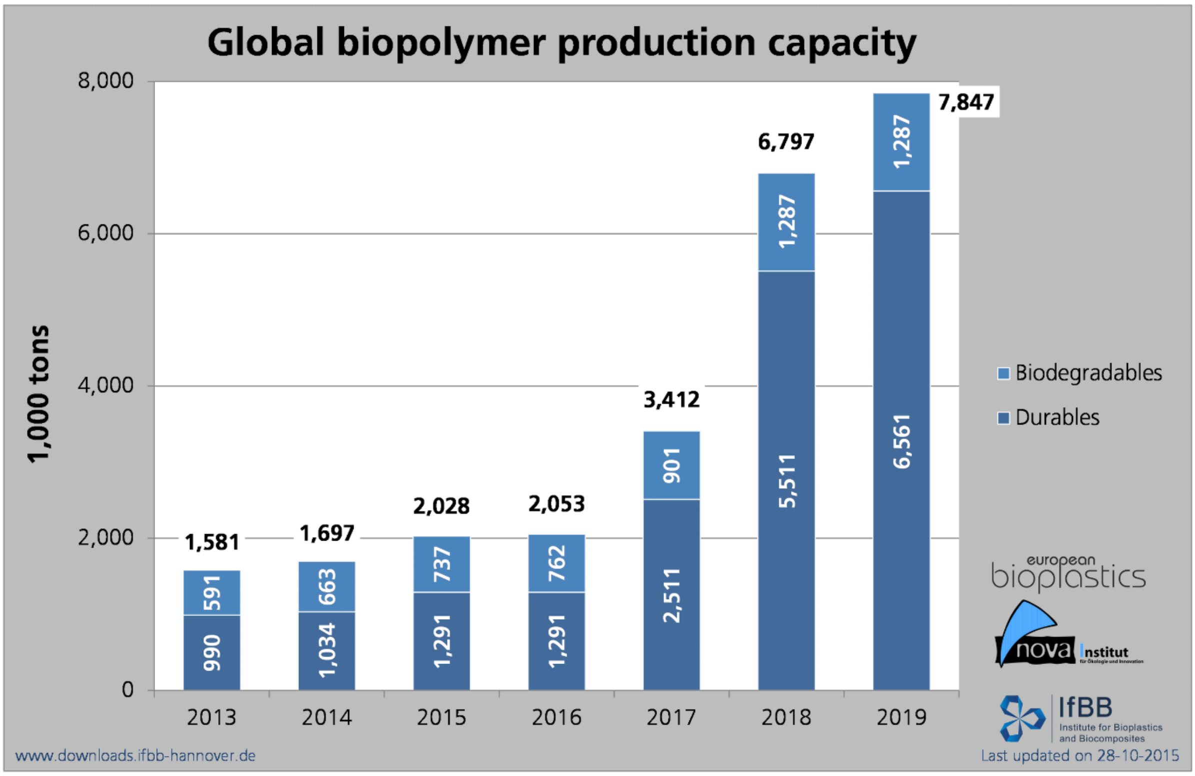


Figure 11: Global biopolymer production capacity (IfBB, 2016)

The growth rate of the biopolymer market is affected by state policy, technology, feedstock cost, competition (biomass versus fossil fuels), crude oil prices, and consumer acceptance among others (Dammer, et al., 2013). It has, however, been interesting to note the continued growth in the bioplastics market in spite of the decreasing fossil fuel price (European Bioplastics, 2015).

The production growth is dominated by biobased and non-biodegradable products such as biobased PE and biobased PET due to the aforementioned advantages in Table 41 available for these 'drop-in' biobased products.

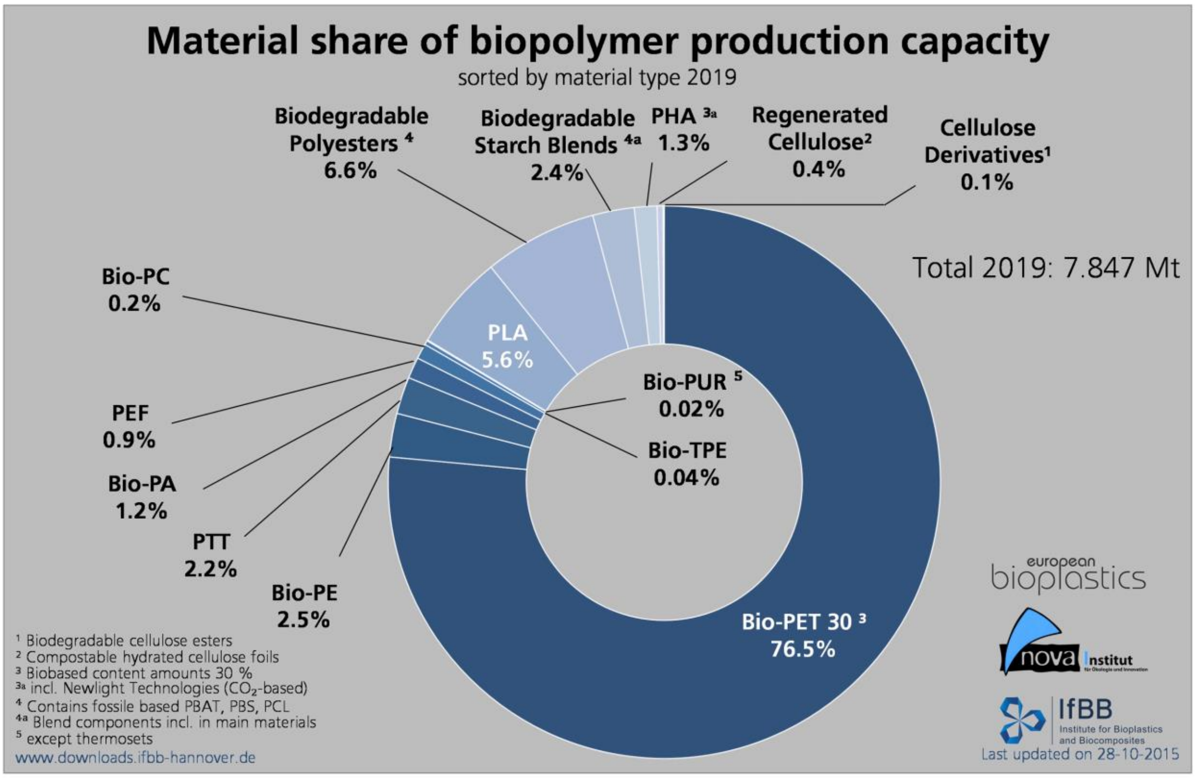


Figure 12: Forecast material share of biopolymer production capacity by material grade 2019 (IfBB, 2016)

However, the production of biobased and biodegradable plastics such as PLA, PHA and starch blends is expected to double from 0.7 million tonnes in 2014 to over 1.2 million tonnes in 2019 (European Bioplastics, 2016).

The data research done in conjunction with the research institutes IfBB – Institute for Bioplastics and Biocomposites (University of Applied Sciences and Arts Hannover, Germany) – and Nova-Institute (Hurth, Germany) concluded that the major market sector for bioplastics remains the packaging industry accounting for over 70% (1.2 million tonnes) of the overall bioplastics markets (European Bioplastics, 2016).

5.3 Biobased Building Blocks

Chemical building blocks consist of a range of molecules that can be converted into secondary chemicals and intermediates that, in turn, can be used in manufacturing industries. Interest in biobased chemical building blocks mostly lies in the production of biobased polymers, lubricants and solvents. Drop-in biobased chemicals can be used in an already established spectrum of products derived from petrochemicals and their associated value chains, thus they carry less financial and technological risk than novel biobased chemicals (BIO-TIC, 2014). However, they are more susceptible to competition than new compounds with novel properties.

5.3.1 Biobased chemical platforms

Owing to their ability to replace petroleum derivatives, biobased production of platform chemicals has increasingly been gaining interest. However, this necessitates the development of efficient cost-effective production strategies and optimisation of downstream processes along with the possibility of retrofitting within existing industrial infrastructure.

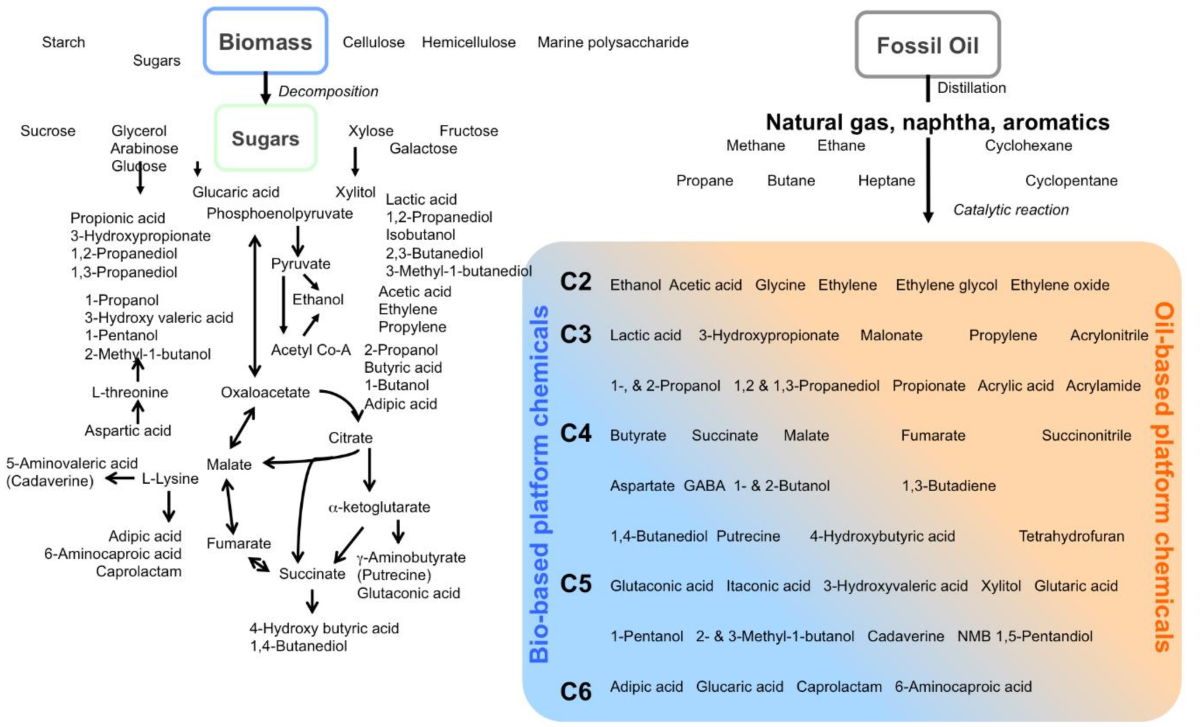


Figure 13: Replacing oil-based platform chemicals by biobased platform chemicals production (Jang, et al., 2012)

Figure 13 illustrates the potential of the biobased chemical platforms that can essentially deliver the same or equivalent petroleum derivatives or building blocks produced by the petrochemical production platform. The orange shading shows the various petroleum-derived chemicals used as precursors for producing platform chemicals. The blue shading shows the different platform chemicals that can be produced from biobased production. The blue shade replacing the red shade is indicative of the possibility of replacing petroleum-derived chemicals by their biobased counterparts. On the left panel of the diagram, the network of arrows indicates simplified biosynthetic networks that can result in the production of biobased platform or intermediate chemicals in microorganisms (Jang, et al., 2012).

5.3.2 Building blocks and monomers as a precursor of polymers

Based on the characteristics of biobased building blocks and platform chemicals and hence the nature of the bond governing polymerisation (e.g. amide-, ester- and C=C bonds), several classes of polymer compounds are available with individual polymers within these classes providing a diverse range of properties. This is shown in Figure 14.

The most common building blocks used in condensation polymerisation reactions are dicarboxylic acids (oxalic acids, malonic, succinic, glucaric, adipic, fumaric and malic acids), diamines (ethylenediamine, cadaverine and putrescine), diols (ethylene glycol, propanediols and butanediols) and aldehydes (formaldehyde) (Jang, et al., 2012). Amines and carboxylic groups from diamines and dicarboxylic acids can form amide bonds during the polymerisation of polyamide production. Ethylene, which has a carbon-carbon double bond, can polymerise to make PE.

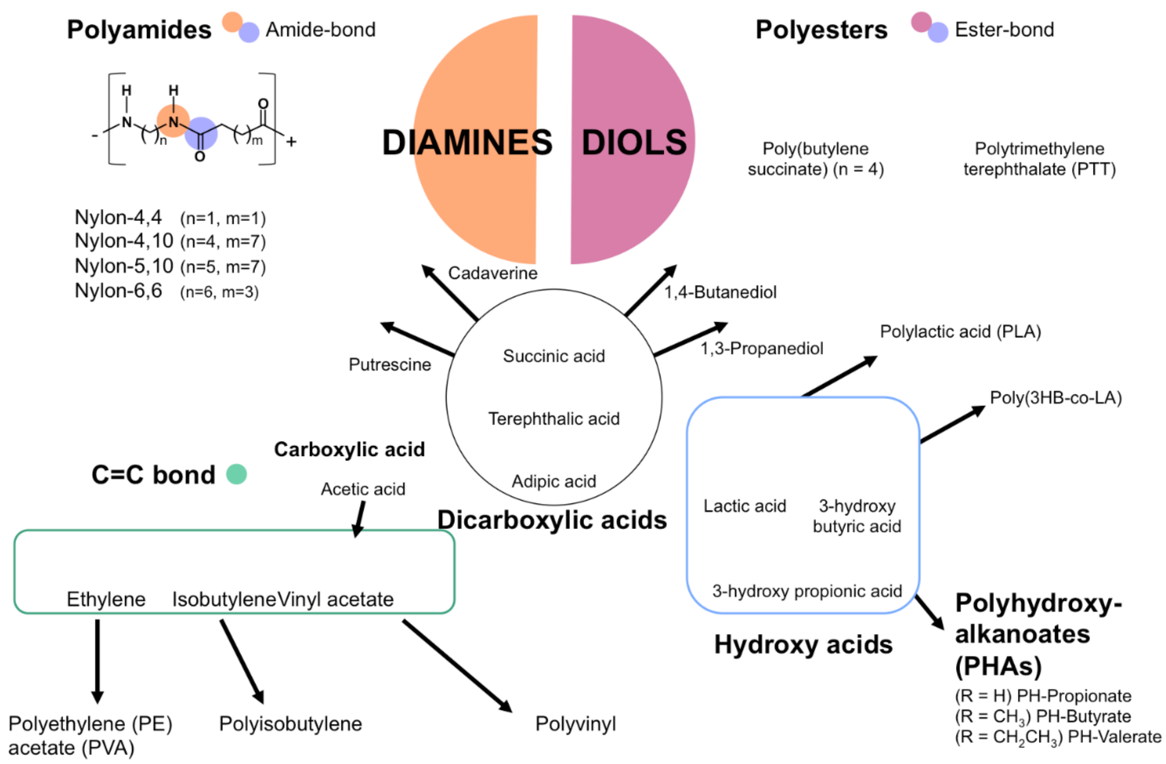


Figure 14: Various polymerisation schemes for generating platform and chemical block chemicals (Jang, et al., 2012)

5.4 Biopolymers from Wastewater and Their Significance in Industry

Industrial and agricultural wastewater usually contains a plenitude of possible substrates such as sugars and organic acids for fermentation by microorganisms, which can fit in the metabolic pathways shown in Figure 13. Polymers produced from wastewater may not be acceptable in the food and pharmaceutical industry but are suitable for the packaging, fittings, apparel and automobile industry. In all cases, using a waste stream as feedstock has a number of challenges. Wastewaters are often considered as receptacles for varied waste, which may lead to the presence of noxious pollutants or inhibitors compromising the functionality of the microorganisms. Further variability in the flow rate and composition of waste streams may lead to difficulty in reproducing and controlling the process. Among the keys to successful implementation of WWBRs is the selection biopolymers that can be readily produced from wastewater and bioreactor designs that facilitate process robustness. As explained in Section 2.3, the WWBR is a relatively new concept that is only starting to gain momentum globally with the vision of closing resource cycles, exploiting the value of wastewater components along with the production of bioproducts and recovery of clean water.

The market analysis demonstrates that biobased counterparts of petroleum plastics (drop-in biopolymers) are currently the front runners in terms of bioplastics development and large-scale production. While it is recognised that biobased plastics such as bioPET that drop in to current value chains may more easily be marketed, these are not considered here. Referring to the material coordinate in Figure 10, preferred biopolymers that adhere to the WWBR vision are biobased and biodegradable, such as PLA and PHAs. Compared to PLA, PHAs are considered more versatile with a range of applications in almost all areas of conventional plastics since there are at least 150 monomers of PHA as opposed to the monomeric (D- and L-lactic acids) structure in PLA (Chen, 2009). Section 5.4.1 expands on PHAs and explores producing them from wastewater as an example of a potential WWBR product. PGA is considered in Section 5.4.2 as another example of a polymer in this category, with certain differences from PHAs in terms of DSP and the option to use as is.

5.4.1 PHAs

PHA is a group of biobased and biodegradable polymers that have a wide variety of physical and chemical properties resembling petroleum plastics. PHAs can be tailored to meet end needs by incorporating different monomers. This gives PHAs the potential to replace petroleum plastics in various applications (Chen, 2009). Table 43 shows various applications of PHAs; they are among the most sought-after biobased and biodegradable polymers.

Table 43: Applications of PHAs in various industries (Chen, 2009)

Applications	Examples
Packaging industry	All packaging materials that are used for a short period of time, including food utensils, films, daily consumables, electronic appliances etc.
Printing and photographic industry	PHAs are polyesters that can be easily stained.
Other bulk chemicals	Heat adhesives. Latex, smart gels. PHA nonwoven matrices can be used to remove facial oils.
Block copolymerisation	PHAs can be changed into PHA diols for block copolymerisation with other polymers.
Plastic processing	PHAs can be used as processing aids for plastic processing.
Textile industry	Like nylons, PHAs can be used as processing aids.
Fine chemical industry	PHA monomers are chiral R-forms that can be used as chiral starting materials for the synthesis of antibiotics and other fine chemicals.
Medical implant biomaterials	PHAs are biodegradable and biocompatible and can be developed into medical implant materials. PHAs can also be turned into drug controlled-release matrices.
Medical	PHA monomers, especially R3HB have therapeutic effects on Alzheimer's and Parkinson's diseases, osteoporosis and even memory improvement etc.
Healthy food additives	PHA oligomers can be used as food supplements for obtaining ketone bodies.
Industrial microbiology	The PHA synthesis operon can be used as a metabolic regulator or resistance enhancer to improve the performance of industrial microbial strains.
Biofuels or fuels additives	PHAs can be hydrolysed to form hydroxyalkanoate methyl esters that are combustible.
Protein purification	PHA granule-binding proteins phasin (PhaP) are used to purify recombinant proteins.
Specific drug delivery	Coexpression of PhaP and specific ligands can help achieve targeting to diseased tissues.

To date there are about 150 different variations of PHAs produced by using different monomers (Bernard, 2014; Braunegg, et al. 1998; Chee, et al. 2010). PHAs come from a family of optically active biological polyesters that contain hydroxyalkanoic units in the R-configuration because of the stereospecificity of the enzymes involved in synthesis (Garate, 2014). Most PHAs are aliphatic polyesters of carbon, oxygen and hydrogen as shown in Figure 15 (Braunegg, et al., 1998) where, *R* is the side chain on the monomer, *n* defines the length of the monomer and *m* is the number of monomeric units in the polymer chain. Both *n* and *R* determine the type of hydroxyalkanoate monomer unit. PHAs have been studied extensively due to their close resemblance to conventional plastics (Loo & Sudesh, 2007).

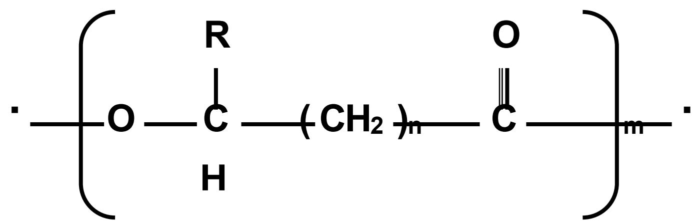


Figure 15: General structure of PHAs (Ebnesajjad, 2013)

An imbalanced growth condition in the form of a limiting nutrient like nitrogen, phosphorus, sulphur, oxygen or magnesium in the presence of excess carbon triggers the polymerisation of soluble carbon intermediates into water-insoluble molecules like PHAs (Annuar, et al., 2008). By accumulating PHAs, microorganisms have a natural reserve of carbon and energy. On restoring the limiting nutrient, the PHAs can be degraded by intracellular enzymes and used as a carbon or energy source (Lee, 1996). PHA synthesis relies on important biochemical pathways such as the tricarboxylic acid cycle, fatty acid degradation (β-oxidation) and fatty acid biosynthesis. Numerous studies have shown that PHAs can be readily produced from activated sludge biomass using VFAs as carbon substrates, as well as from simple sugars, oils and a variety of waste feedstocks such as molasses, milk waste and others (Verlinden, et al., 2007). PHAs are produced intracellularly and serve as storage compounds in microorganisms, which can often also provide biological phosphorus removal, making PHAs interesting candidates in wastewater treatment (Satoh, et al., 1999). PHA production can be exploited by enriching the activated sludge with PHA-producing microorganisms and having adequate carbon substrate and oxygen concentration in the presence of a limiting nutrient. Chua et al. (2003) investigated the feasibility of PHA production using activated sludge. They concluded that with the required process optimisation, PHA production was an added benefit to waste treatment in the form of waste conversion to a valuable product.

Potential wastewaters for PHA production are VFA mixtures (acetate, propionate), food waste, olive and palm oil mill effluents, sugarcane molasses, diary effluents, paper mill effluents, fruit and tomato cannery effluents, brewery effluents and municipal wastewaters. Regarding process optimisation where wastewaters are rich in organic loading, more conventional approaches to PHA production can be used. Under these conditions, it is essential to use a microorganism giving a high PHA productivity to sustain its economic production, i.e. a cheap or free carbon source alone is insufficient (Theobald, 2015).

5.4.2 PGA

PGA, an extracellular biopolymer, is produced by many *Bacillus* species and was discovered as a capsule surrounding *Bacillus anthracis* by Ivanovics and co-workers in 1937. In 1942, Bovarnick discovered that *Bacillus subtilis* can produce PGA as an extracellular by-product of fermentation (Goto & Kunioka, 1992). It is a biodegradable anionic substance that consists of D- and L-glutamic monomers held together by γ-amide linkages between the carboxylic groups, as shown in Figure 16.

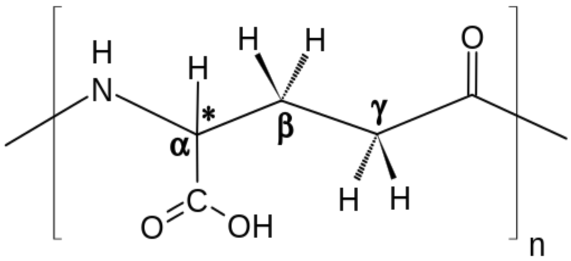


Figure 16: Chemical structure of PGA (Wikimedia, n.d.)

This water-soluble, non-toxic polyamino acid has potential for a diverse set of industrial applications as it has a wide range of functions (Shih & Wu, 2009). It has been successfully used in the food, wastewater and medical industries (Ogunleye, et al., 2014) as shown in Table 44. It is currently expensive to produce, with the main costs associated with purification (Kumar, et al., 2014). In less pure form, it can be used as a flocculant (Carvajal-Zarrabal, et al., 2011) and soil conditioner (Shih & Wu, 2009).

Table 44: Applications of PGA in various industries (Ogunleye, et al., 2014)

Applications	Function	Reference
Biopolymer flocculant	PGA supplemented with cations show a high flocculating activity.	(Bajaj & Singhal, 2011)
Heavy metal removal	The covalent incorporation of PGA on to a microfiltration membrane results in a high metal sorption ability.	(Bhattacharyya, et al., 1998)
Dye removal	PGA could be used to remove basic dyes from solution. At a pH of 1, the dyes can be removed from the PGA, making the PGA available for reuse.	(Inbaraj, et al., 2006)
Medical metal chelator	PGA-coated super-paramagnetic iron oxide NPs demonstrated high heavy metal removal efficiency from simulated gastrointestinal fluid and a metal solution.	(Inbaraj & Chen, 2012)
Medical biological adhesive	An aqueous solution of PGA and gelatine can be used to form hydrogels in the presence of water-soluble carbodiimide. This can be used as a tissue adhesive.	(Otani, et al., 1999)
Medical calcium absorber	The presence of PGA in the intestine increases calcium absorption by inhibiting the formation of an insoluble calcium complex with phosphate.	(Tanimoto, et al., 2007)
Food texture enhancer	Wheat bread supplemented with PGA enhances the thermal and rheological properties of the dough.	(Shyu, et al., 2008)
Food oil-reducing agent	Food supplemented with PGA reduces oil uptake in deep frying.	(Lim, et al., 2012)
Biodegradable plastic	Esterified PGA has shown to be a good thermoplastic. PGA's ester derivatives have the ability to form fibres and films.	(Kubota, et al., 1995) (Shih & Wu, 2009)
Biocontrol agent	A combination of lipopeptides and PGA increase nutrient consumption in seedlings.	(Wang, et al., 2008)

Applications	Function	Reference
Glucose sensor	PGA film helps with the immobilisation of glucose for glucose sensor preparation.	(Yasuzawa, et al., 2011)
Antibacterial activity	PGA has demonstrated activity against *Salmonella enteritidis* SEM 01 and was compared with commercial antibiotics linezolid, cefaclor and cytocompatible.	(Inbaraj, et al., 2011)
Treatment of xerostomia (dry mouth)	The presence of PGA in the mouth aids with salivary secretion.	(Uotani, et al., 2011)

The *Bacillus* species is a well-known robust workhorse that is used in many industrial applications such as production of heterologous proteins, antibiotics, nucleotides, biosurfactants, biofuels and biopolymers (Meissner, et al., 2015) They produce PGA under starvation as a glutamate source (Ogunleye, et al., 2014) and for protection under harsh conditions (McLean, et al., 1990). The industrial production of PGA is traditionally by running fermentation in a CSTR with a steady nitrogen source (Bending, et al., 2014). PGA-producing bacteria can be grouped into two categories: (i) L-glutamic acid dependent microorganisms: PGA cannot be synthesised without the presence of this amino acid in the cultivation medium; and (ii) L-glutamic independent bacteria: they are able to synthesise the polymer in the absence of L-glutamic acid in the medium because of the de novo pathway of L-glutamic acid synthesis (Xu, et al., 2005).

PGA biosynthesis takes place in two steps. The first step involves the synthesis of L- and D-glutamic acid monomers. The second step joins these monomers into a polymer. The size of these polymers differs from organism to organism and also depends on the nutrients in the cultivation medium (Bajaj & Singhal, 2009). PGA is produced mainly from citric acid and ammonium sulphate found in the tricarboxylic cycle in the mitochondria of cells as shown in Figure 17. Citric acid is metabolised to isocitric acid and then α-ketoglutaric acid which is a glutamate precursor (Moraes, et al., 2013).

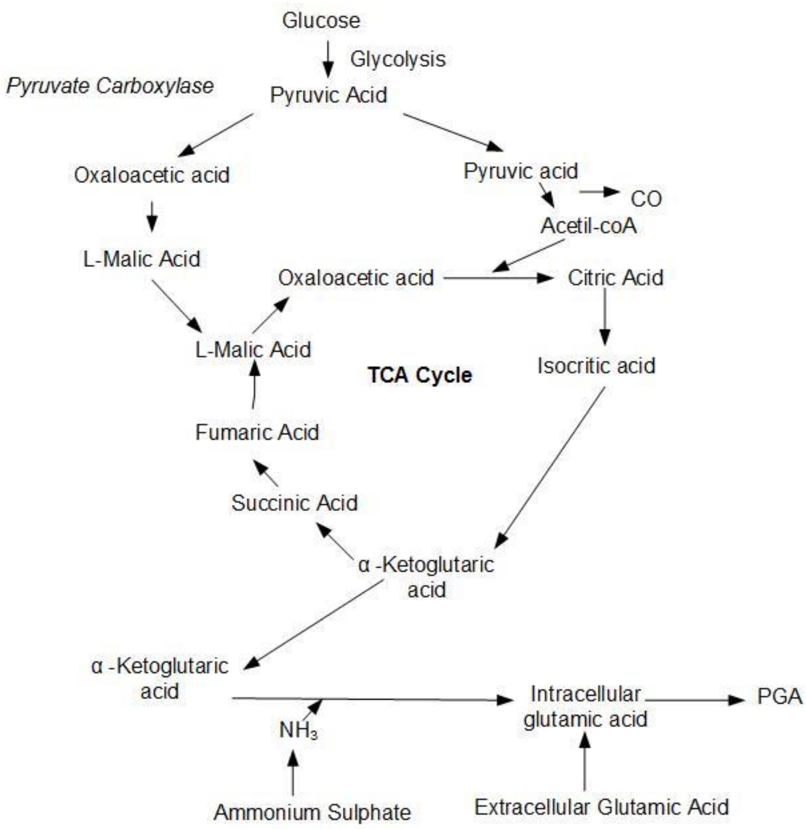


Figure 17: Pathway for PGA production (image redrawn from Moraes, et al. (2013))

Due to its potential for wastewater treatment and range of other possible uses, it will be beneficial to produce this polymer in the WWBR. The polymer's properties (Margaritis, 2003) and protective function towards the bacteria producing it make it likely that its production from wastewater by a mixed microbial consortium could be successful.

Research on PGA has largely been focused on sterile bioprocesses at laboratory scale (Cromwick, et al., 1995). Some research investigated production from waste solids, notably swine manure (Chen, et al., 2005), cow manure (Yong, et al., 2011) and SSF using soybean powder and wheat (Xu, et al., 2005). One study used untreated cane molasses at laboratory scale (Zhang, et al., 2012), but to date no publications have been found on producing PGA from wastewater. This was extensively investigated in a previous WRC project K5/2000 (Madonsela, 2013; Verster, et al., 2013).

In order to further the ability to select the correct bioproduct for each WWBR, more experimental work is needed to investigate the production of these products using local microbial cultures with wastewater feedstock. The start of an experimental study in the production of PGA using local microbial cultures and moving towards testing on wastewater as growth medium is reported in Appendix D.

5.5 Biobased Products for the Integrated WWBR

In an integrated WWBR, the whole range of potential products must be assessed so that the entire process produces an adequate range of biobased products, while simultaneously breaking down and consuming the nutrients available in the feedstock to produce the compliant effluent water. This chapter examined the potential of various biobased products focusing particularly on biopolymers likely to be associated with the functioning of the bacterial bioreactor, positioned to deplete the organic loading of the wastewater.

The process followed here demonstrates how, beginning with a broad overview of common products (Section 5.1), the most suitable suite of product types can be selected for each bioreactor. This selection can take the potential for use within the WWBR or the parent process into account, and ensure a good spread of output from the biorefinery as a whole.

Within each product type selected, a procedure can be employed similar to that used here, enabling the choice of specific product. This will include a careful analysis of the potential products within that category, detailing the various methods of grouping the potential products.

Some additional assessments will then have to be made within each grouping of products. The specific products will have to be evaluated in terms of market trends (global, national and local). The technological position of each must then be appraised in terms of both the availability of commercial scale technology for production and the technical readiness of the potential market for absorption of the product. For some products, the sociological positioning of the product as produced from wastewater will also have to be considered.

The way, this consideration of product options is incorporated within the whole conceptualisation of a particular WWBR, which forms part of the exploration of the way forward in Chapter 9.

6 REVIEW OF POTENTIAL BACTERIAL BIOREACTORS: CRITERIA FOR SELECTION

Owing to the typically dilute nature of wastewater streams, their variability, the impracticalities of sterilisation, and the need to handle large effluent volumes, the selection of appropriate bioreactors for the WWBR application depends on meeting multiple process criteria. The particular technologies available for each of the different types of bioreactor, bacterial, algal, macrophytic and fungal (outlined in Section 3.4), must be assessed with the constraints of the WWBR in mind. A detailed assessment of bacterial bioreactors is presented in this chapter as a paradigm for bioreactor selection.

To aid in this selection, the necessary criteria for WWBR reactors are developed in Section 6.1. Current bacterial bioreactor technology used in South Africa's WWTWs is reviewed in Section 6.2. The various technologies are assessed in Section 6.3 against the criteria specified, and suitable bioreactor technologies for application in WWBRs are listed and reviewed. The bacterial bioreactors selected as suitable for application in WWBRs are detailed in Section 6.4.

6.1 Challenges for Bioproduction from Wastewater

Current wastewater bioreactors are well designed to achieve nutrient removal from the wastewater with limited design towards product recovery. The main focus is the delivery of clean water. From a bioprocess engineering perspective, using wastewater streams presents unique challenges in terms of product recovery. Traditional product-focused bioreactor optimisation aims to reduce the bioreactor volume to reduce the energy invested per unit product. It also aims to achieve a high biomass concentration, which results in lower DSP cost per unit product (Richardson, 2011). Using wastewater as raw material is counterintuitive as it combines wastewater treatment and bioprocess approaches. Intentionally innovative bioreactor design contributes to the viability of using wastewater as a low cost and highly available raw material.

WWBRs are not suited to all types of product. The chosen products are required to meet commodity market needs, be suited to the utilisation of organics from large stream flows and serve an ecological function for the microorganism to drive its competitive advantage (Kleerebezem & Van Loosdrecht, 2007; Verster, et al., 2014). Bioreactor design needs to enhance this ecological niche to produce the desired product. These challenges are listed in Table 45 along with design and operational requirements needed to address them. These are investigated further in the following sections.

Table 45: Wastewater biorefinery bioreactor design requirements

#	Requirement	Comply?
Large Volume		
1	Decouple hydraulic and solid retention times	✓
2	Continuous or semi-continuous (cannot store flows)	✓
3	Think big! Commodity rather than niche	✓
Complex, Variable		
4	Influence microbial community, non-sterile	✓
5	Give advantage to product: create ecological niche	✓
Environment		
6	Water released into environment eventually	✓
Downstream Processing		
7	Product formation in different phase?	✓
8	Can product be recovered?	✓
9	Reactor design conducive to reducing DSP load?	✓

6.1.1 Large volumes of wastewater

Very low concentration of valuable product

One significant challenge of bioprocesses is the dilute nature of the medium, with both substrates and products present at very low concentration; typically, less than 5% of the total dissolved solids. When using waste streams like municipal wastewater that can be a thousandfold more dilute, this aspect is even more challenging. The apparent biocatalyst concentration must be increased to enhance process intensity over the current approach of huge dilute vats of water by allowing a reduction in residence time. In addition, adequate nutrient provision to the cells must be ensured without compromising the ability to recover the product. This defines the mass and energy transfer needs. Aeration and heat transfer in dilute media is inefficient and energy intensive. By using biomass retention, these requirements can be better managed.

With respect to the product, for cost- and energy efficient downstream processes, localising product in an accessible location with high apparent concentration is preferred. Many processes currently use standard bioreactor setups and optimise the DSP subsequent to production. Bioreactor design has scope to facilitate DSP and can have a greater impact on overall process optimisation (Richardson, 2011). The entire process needs integrated optimisation, cognisant of the performance at the level of unit operation, process operation and systems operation (including aspects outside of the process).

Aeration

Oxygen is sparingly soluble in water. In the typical high-volume low-concentration bioprocesses, energy for aeration is the biggest burden in terms of economics and sustainability. In wastewater treatment, aeration can be up to 70% of the operating costs (Tchobanoglous, et al., 2003). Oxygenation often controls stoichiometric limitation, and frequently also governs the reaction rate (Bailey & Ollis, 1986). Aeration in biofilms presents a special challenge due to the additional barrier that the thickness of the biofilm layer poses to oxygen diffusing through to the deeper biomass.

Aeration can also be used as a mixing device. With biofilms, the shear associated with aggressive airflow can be used to slough off biomass as a rudimentary type of DSP. Types of aeration include separate aeration of the flow of recycle, aeration in the support medium itself and aeration of the biofilm (Henze, et al., 2002).

6.1.2 The need for biomass retention

When the substrate concentration in the feed is high (>10 g COD/ℓ) and rapidly growing organisms (growth rate >0.1 /h) are used, there is no need for biomass retention from a biomass concentration perspective (Figure 18) (Nicolella, et al., 2000). In dilute wastewater treatment, biomass retention is advantageous as conversion is limited by the amount of biomass present and retention allows the necessary increase in biomass concentration (Nicolella, et al., 2000). This may be applied to the retention of an inoculated or a natural mixed microbial community. Biomass retention also facilitates the effective decoupling of the hydraulic and solid retention time which may be used to improve bioreactor volumetric conversion capacity.

Most WWTWs employ activated sludge. The resultant flocs require large settling ponds. The two approaches that are most promising for WWBR bioreactor design are generating conditions suitable for static biofilms with slightly higher flow rates, and particle biofilms occurring at slightly higher substrate concentrations. At high substrate concentrations, sufficient biomass or product may be formed to justify conventional bioprocess approaches using single cells.

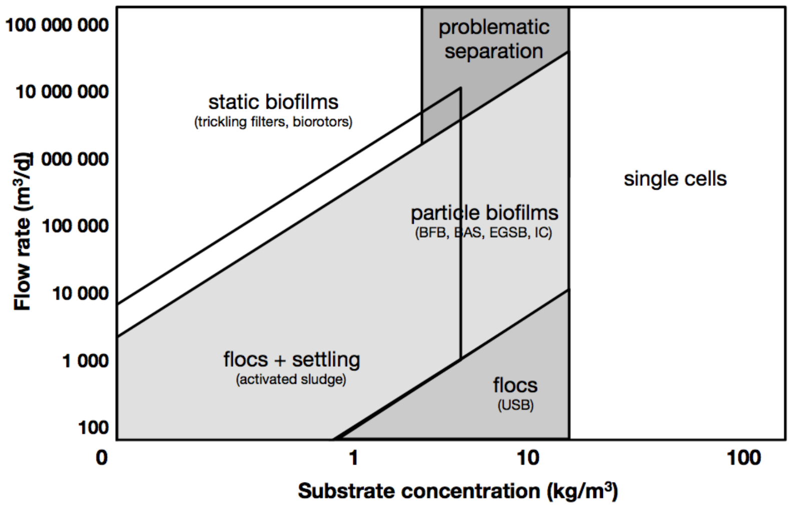


Figure 18: Concentration-flow rate phase diagram for application of floc and biofilm bioreactors (adapted from (Nicolella, et al., 2000))

If a bioprocess is designed to produce and isolate a product from a low substrate stream and treat water, retention of the biomass and product recovery are essential. This involves decoupling hydraulic residence time and biomass residence time. Biomass retention is used to increase the apparent biocatalyst concentration and ensure separation of biomass from the liquid stream. Accumulation of the product into a phase other than the dilute liquid phase may also be used to concentrate the product.

Biomass retention can be established by using recycling loops, immobilisation through biofilm formation, granulation, retaining the biomass in suspended form through selective membranes, or a combination of these. In wastewater treatment, immobilisation typically relies on the controlled growth of a biofilm or the formation of flocs or aggregates of biomass. Cell entrapment in immobilisation matrices is more common in bioprocess applications. Flocs are included as a form of biofilm without solid support in this review to allow inclusion and comparison of the granular sludge with other biofilm techniques. Filters may require less maintenance if the biomass is not suspended, for example through combining cell immobilisation with filtering or by including a settling stage prior to filtering. If the product is cell-associated, retention of the biomass forms the first stage of product concentration and the retention medium needs to be designed to be suitable for biomass recovery.

6.1.3 Design for DSP

A fundamental consideration in the feasibility of bioprocess from dilute streams from both an economic and environmental point of view is in the approach to DSP. In these dilute systems, recovery of both the product and the water is essential. The latter may be recycled back to the process upstream of the WWTW or recovered as water of useable quality: ”fit for purpose”. In a systems approach, the recovery and quality of both water and co-product need to be considered. There are three main requirements to realise effective product formation and recovery from dilute (waste) streams:

- Decouple hydraulic residence time and biomass residence time. Biomass retention to increase the apparent biocatalyst concentration can also contribute to concentrating the product into a different phase.
- Ensure adequate nutrient provision to the cells without excessive energy requirement for mass transfer, and without compromising the ability to recover the product.
- Design for DSP. Bioreactor design and choice of the biological system used affect the cost of DSP significantly. In dilute waste streams, many DSP methods are not cost effective, as the combination of volume processed and energy requirement per unit volume is too great. The need for centrifugation, for example, is a challenge that cannot be addressed at DSP level, but needs to be prevented through choice of system and bioreactor design. Concentration of the product into a separate phase, either the gas phase or settleable biomass phase, is proposed to facilitate product recovery.

Design of cell retention and recovery can be used in combination for improved productivity and facilitation of DSP. If the product is soluble, separation of the biomass from the liquid usually precedes purification steps such as precipitation, ultrafiltration and chromatography, unless an affinity step can be implemented. However, the solid-liquid separation is still needed for water purification. Where chemicals are added to precipitate product, biomass should be removed first to prevent contamination of the product. It should be noted that the need for adding chemical reagents such as precipitation agents is not a preferred route to recover products from dilute suspension.

While biomass retention is important for reasons outlined in this review, it serves different functions depending on where the product is located, and whether the biomass itself is recovered or not. This determines bioreactor selection. Figure 19 is an initial guideline for WWBR bioreactor selection.

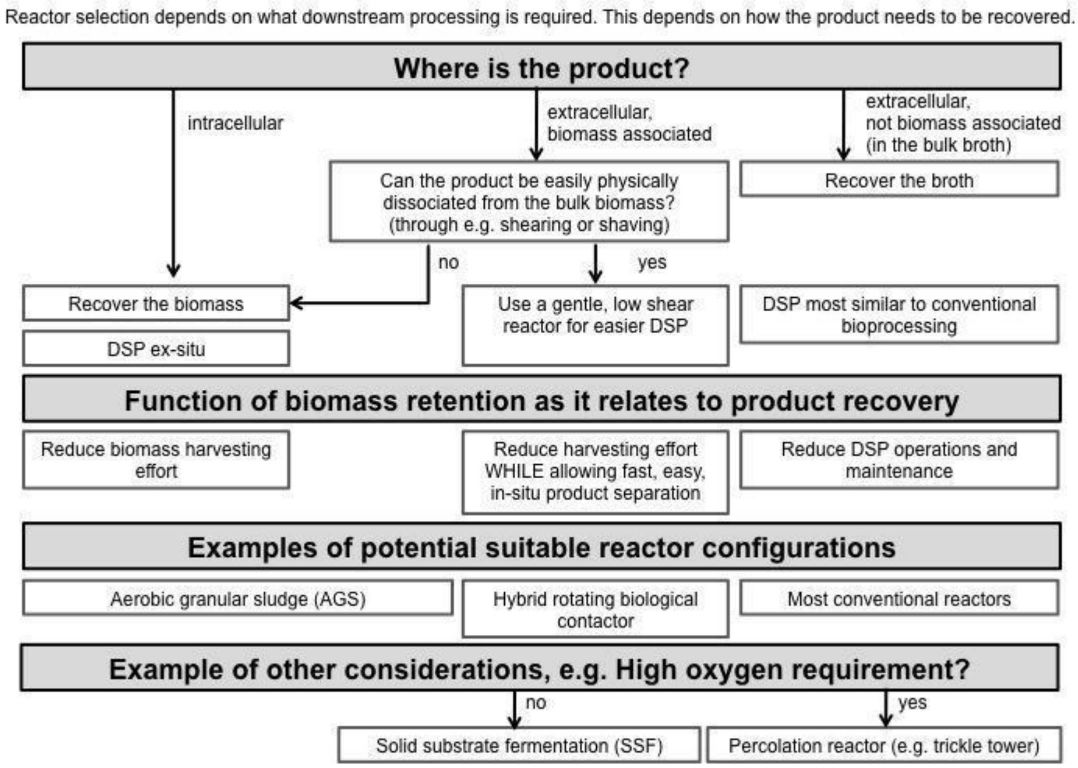


Figure 19: Suggested guideline for WWBR bioreactor selection (Verster et al., 2013)

6.1.4 Release into the wider environment

Conventional bioprocessing requires a homogeneous, highly controlled environment, but wastewaters tend to be more complex and heterogeneous. As the water is destined for discharge to the environment, any additives to improve the characteristics of the stream need to be non-hazardous. The volume of the stream precludes extensive stream modification. Depending on the robustness of the organism, environmental regulation and social acceptability, the use of genetically modified organisms may also be precluded. Further, sterilisation is typically not practical. This results in limited scope for modification of the microbial community in the manner currently favoured for bioprocess applications. Instead, the most robust and resilient microorganisms make up a mixed community that is well adapted to the physicochemical environment in which it exists and is able to withstand shock loads and hostile environments (Chen, 2013).

Reducing the pathogen loading in the water that is released to the environment relies on the production and recovery of products. Although bioreactor design may be oriented towards reducing DSP costs through a product that can be recovered from a concentrated stream (Section 6.1.3), there can be significant advantage to bioproduction processes including DSP of the entire stream for product recovery because of the reduction of pathogens in the effluent (Stephenson, et al., 2000).

6.2 Reviewing and Assessing Bioreactors Currently Used in Wastewater Treatment in South Africa

Through WRC projects K5/1732 (Brouckaert, et al., 2013) and K5/2000 (Verster, et al., 2013), it has become evident that the implementation of the WWBR concept benefits from adhering to key principles in the selection for each unit operation of the system; bioreactor selection is a crucial element of this. The key principles established in Section 6.1 are:

- The selection of a product existing in a different phase to the aqueous nutrients to facilitate product recovery.
- The selection of a microbial phase favouring retention in the system to allow the decoupling of the biomass and hydraulic residence times.
- Application of non-sterile bioproduction systems.
- The utilisation of a multicomponent system allowing the integrated optimisation of the system rather than direct competition between water quality and product formation.

These principles provide the framework for bioreactor selection to convert organics to product. Through selected case study(s), the role of bioreactor design and configuration can be explored. The principles of integrated optimisation, including product recovery and product formation operations, should also be explored.

Table 46 provides an overview of technologies and bioreactor types used in current WWTWs in South Africa, and their principle of operation. Their suitability for use in a WWBR, as defined by the selection criteria of Table 45, is assessed. The number of categories that each bioreactor type or technology fulfils is indicated. The bioreactors suitable for WWBRs are reviewed in detail in Section 6.3 to inform final bioreactor selection, which is detailed in Section 6.4.

The list of requirements rendering the bioreactor type and technology useful has been numbered in Table 45. In Table 46, the number of each category that the bioreactor or technology fulfils is shown and its relevance for application in WWBRs indicated based on the number of the categories fulfilled. The focus was on the principle of operation of the bioreactors: whether they would result in easier DSP (Category 7 to 9) and their potential for retrofitting for use in the WWBR. Based on the findings of Verster et al. (2013) in Section 6.1.3, the highest priority requirements were outlined to be the decoupling of hydraulic and solid residence times (1), and the DSP requirements (7 to 9).

The existing technologies used in South African WWTWs that did not fulfil Category 1 and Categories 7 to 9 were excluded from the shortlist. There is little sense in selecting a technology that increases the financial investment based on its principle of operation and reliance on the traditional energy intensive DSP, which is known to be costly. With this in mind, activated sludge and BNR were not considered further.

Table 46: Summary of bioreactor types or technologies used in wastewater treatment and their suitability to be used in WWBRs

Bioreactor Type/ Technology Used		Principle of Operation	Number of the Nine Requirements Fulfilled	Suitable for Use in Wastewater Biorefineries?
A	Activated sludge (in CSTR)	This technology uses suspended growth bioreactor technology. It consists of flocculated slurry of microorganisms that are used to remove soluble and particulate biodegradable matter from the wastewater. The type of bioreactors used are typically CSTRs in various configurations depending on the conditions desired and or level of treatment [1]. It is one the most common forms of wastewater treatment technologies used in South African municipalities [1, 2, 3].	2, 3, 4, 6 (4/9)	X
B	BNR (in CSTR in series with recycle)	BNR is similar in operation to activated sludge systems. These systems are some of the most complicated technologies used for wastewater treatment, and come in a variety of configurations. BNR processes are divided into different zones where the biological environments are different and allow for removal of nitrogen and/or phosphorus [1]. BNR usually consists of CSTRs in series with recycles incorporated to achieve the different zones.	2, 3, 4, 6 (4/9)	X

Bioreactor Type/ Technology Used		Principle of Operation	Number of the Nine Requirements Fulfilled	Suitable for Use in Wastewater Biorefineries?
C	Packed bed reactor (PBR)	PBRs fall under the category of submerged attached growth bioreactors. Granules used to create the packed bed are small in size and typically only a few millimetres in diameter. The particle carriers used can be plastic, rounded sand or fired clay. The packed bed acts as a physical filter for particulates, and can be used to oxidise soluble and particulate organic matter and achieve nitrification and denitrification. The flow within the packed bed can be either upward or downward [8].	1, 3, 4, 5, 6, 7, 8, 9 (8/9)	✓
D	Fluidised bed biological reactors (FBBR)	FBBRs are also a type of submerged attached growth bioreactor that has been largely used for the treatment of industrial wastewater. The upward flow of the influent wastewater creates drag forces that suspend the carrier particles upon which the biofilm grows. As the biomass grows, it results in the expansion of the bed height. To prevent the loss of carrier particles and uncontrolled bed expansion, separators are usually included in the process to return carrier particles to the FBBR and remove excess biomass [1, 3].	1, 3, 4, 5, 6, 7, 8, 9 (8/9)	✓
E	Rotating biological contactor (RBC)	RBCs fall under the category of attached growth bioreactors. The microorganisms form biofilms on the disks that are attached to a shaft and rotate in the liquid (wastewater). The shaft and disks are oriented perpendicularly to the direction of the influent. More than one RBC is typically used, which are oriented in series to achieve the desired effluent quality. Oxygen transfer is created by the rotation of the disks that are only partially submerged. They are commonly used by WWTWs [1].	1, 2, 3, 4, 6, 7, 8, 9 (8/9)	✓
F	Trickle bed reactor (TBR)	The TBR, also known as a trickling filter (TF), is a type of attached growth biofilm bioreactor in which the substrate is trickled over a fixed carrier. Air is passed counter-current up the bed where diffusion between the wastewater and biofilm occurs. The TF bioreactors used in industrial applications consist of a recycle stream to improve nutrient removal, as well as a liquid-solid separation unit. It was one of the first technologies used to treat wastewater and is well established and understood [1, 2, 3].	1, 3, 4, 5, 6, 7, 8, 9 (8/9)	✓
G	Membrane bioreactor (MBR)	This technology is a variation of the activated sludge process that includes a liquid-solid separation through the use of filtration membranes (flat sheet or tubular). It achieves a high quality of effluent and is increasingly being used in the WWTWs and in some industries in South Africa [1, 2].	1, 2, 3, 4, 5, 6, 7, 8 (8/9)	✓
H	Moving bed bioreactor (MBBR)	The MBBR process is based on attached growth biofilm principles of biological wastewater treatment. The core of the process is the biofilm carrier particles. While the biofilm is fixed to the carrier particles, it is thoroughly mixed and retained within a bioreactor. Carrier particle circulation within the bioreactor is provided by the aeration system or by mixers (anaerobic conditions) [1, 3].	2, 3, 4, 5, 6, 8, 9 (7/9)	✓
I	Aerobic granular sludge reactor (AGSR)	Dense granules of strong biomass structure are formed, which are essentially aggregates of microorganisms that are densely packed with a much higher settling rate than the conventional sludge, that is so well-known in biological wastewater treatment [4]. From their unique characteristics, the most desirable attribute is their high biomass retention ability, which allows the smaller reactors and shorter hydraulic residence times. Thus far, the sequencing batch reactor (SBR) is the only bioreactor type that has successfully been able to cultivate the granules according to Adav et al. [4]. The bioreactor is very simple in design and is fed discontinuously, although it can be manipulated to operate under continuous flow conditions. These characteristics of the bioreactor, along with the high settling rates of aerobic granular sludge make it an ideal niche to study the formation of products from wastewater in laboratory settings [5].	1, 3, 4, 5, 6, 7, 8, 9 (8/9)	✓

1. Grady, CL, Daigger, GT, Love, NG & Filipe, CDM. (2011). Biological Wastewater Treatment (3rd ed.). London: IWA.
2. DWA. (2008). Municipal wastewater treatment. Gauteng. Retrieved from https://www.dwa.gov.za/dir_ws/wsam/vdfileload/file.asp?val=14&tablename=AsetFiles&fld=ID.
3. Merwe-Botha, M & Quilling, G. (2012). Drivers for wastewater technology selection assessment of the selection of wastewater treatment technology. Retrieved from http://www.wrc.org.za/Knowledge Hub Documents/Research Reports/TT 543-12.pdf.
4. Adav, SS, Lee, D-J, Show, K-Y & Tay, J-H. (2008). Aerobic granular sludge: Recent advances. *Biotechnology Advances*, 26(5), 411-423. doi:10.1016/j.biotechadv.2008.05.002.
5. Johnson, K. (2010). PHA production in aerobic mixed microbial cultures. Technische Universiteit Delft, Kingdom of Netherlands.

6.3 Detailed Review of Shortlisted Bioreactors

A detailed review of the bioreactors selected in Section 6.2 is presented. For each bioreactor type, its general description, physical characteristics, operating conditions, economic requirements, impact on DSP and recovery are considered. The selection of five bioreactors was made based on current technologies that are used by South African WWTWs, new technologies showing promise in large-scale application for wastewater treatment and that also fulfil the requirements for application in the WWBRs space, and finally, that are suitable for large flow rates.

Figure 20 provides a visual representation of the reactors presented in Table 46 regarding product recovery potential and degree of biomass retention. Both of these are important when selecting an appropriate bioreactor technology for the WWBR.

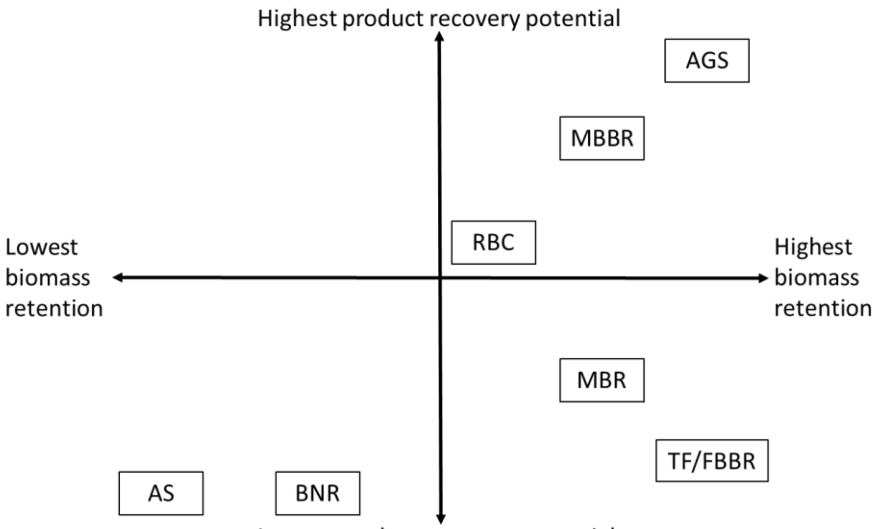
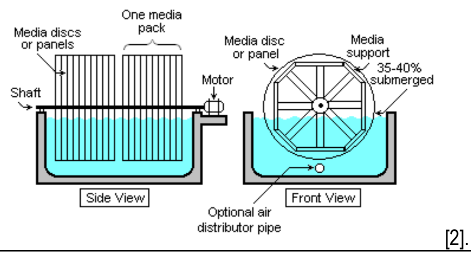


Figure 20: Summary chart of the bioreactor technologies in Table 46 and their compliance with important criteria for application in WWBRs AGS: aerated granular sludge; AS: activated sludge; BNR: biological nutrient removal; FBBR: fluidised bed biological reactor; MBBR: moving bed bioreactor; MBR: membrane bioreactor; RBC: rotating bed contactor; TF: trickle filter (TBR)

The five bioreactors that were selected and assessed are the RBC (Table 47), TBF (Table 48), AGSR (Table 49), MBR (Table 50) and MBBR (Table 51). The PBR has similar principles of operation than TBR, and detail is provided on the last of these only, as it known to be one of oldest and most well understood of wastewater treatment technologies. The tables summarise the main characteristics of these bioreactors in WWTWs. Where possible, South African examples are provided. The main advantages and disadvantages and physical and operational characteristics are also discussed. Associated approaches to use in a WWBR have been considered as has the effect on DSP.

Table 47: Comparison of five bioreactors suitable for WWBRs – RBC

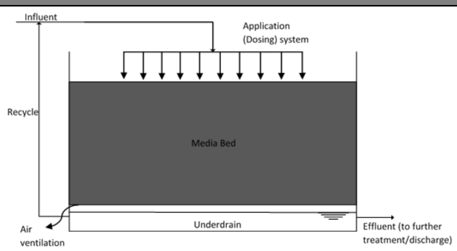
<table>
<tr><th colspan="2">Rotating Biological Contactor</th></tr>
<tr><td>Diagram</td><td> [1] 

[2].</td></tr>
</table>

Rotating Biological Contactor	
Description	The RBC consists of closely packed circular disks with surface areas from approximately 9300 m^3 to 13 900 m^3, made from polystyrene or polyvinyl chloride (PVC). The disks are mounted on a horizontal shaft and submerged (typically 40% of the rotating unit as shown above) in the holding tank containing the wastewater. Typical dimensions of the shaft are 1.52 m to 8.23 m with a thickness of 13 mm to 30 mm. The shaft rotates slowly at between 1 and 2 revolutions per minute. The disks are typically made of high-density polyethylene with UV inhibitors [3].
When or Why Used in WWTWs	RBCs are a type of static biofilm reactor that uses attached growth biological treatment. The RBC process has been used extensively and is a well-established process, for the pretreatment of industrial wastewater, BOD removal, and nitrification and denitrification [3]. This type of bioreactor is used in WWTWs with flows below 40 000 m^3/day as economies of scale are poor. They are typically used to nitrify municipal wastewaters with carbon oxidation and nitrification applications. They have also been used successfully to treat industrial wastewaters with low to moderate strengths of hydrogen sulphide [4].
Advantages	Mechanically simple and reliable. Low energy usage (3.7 kW to 5.6 kW per shaft). Motion of shaft causes aeration by exposure to atmosphere and shear stress. Large-scale operations are successful and well implemented worldwide. Modifications are easy to apply and biomass can be removed easily. Able to handle lower substrate concentrations (preferable) [3, 4, 5].
Disadvantages	Requires good pretreatment and primary clarification to avoid solids in the units. Algal growth has been noticed if units are not covered sufficiently. Lack of understanding of biological process causes system and structural failure. Limited process flexibility. Often more than one unit required, taking up valuable land space [3, 4, 5].
Physical Characteristics	
Reactor Size	Units are typically produced in standard dimensions [4]. Information on typical reactor sizes used in South Africa's WWTWs could not be found.
Arrangement/Configuration	Typical arrangement is in series with stages dependent on the degree of treatment required. Two to four stages have been used to achieve BOD removal, with six or more stages to achieve nitrification. Typical staging arrangements are flow parallel to shafts, flow perpendicular to shafts, step feed flow or tapered feed flow parallel to shafts [4].
Operating Conditions	
Hydraulic Retention Time	Variable. A function of each reactor design and constraints. Also dependent on level of treatment desired. $\Lambda_{H,RBC} = \frac{F}{A_s} \ldots \ (1)$ where A_s is the media surface area and F is the influent flow rate [4].
Organic Loading	Studies on full-scale RBC facilities indicate that oxygen limitations occur at COD soluble organic loading (SOL) of 20 g to 35 g COD/(m^2/day) (SOL value) [4].
Effluent Treatment	Effluent is of the South African general standards for discharge limits [6].
Aeration Requirements	Oxygen is supplied from the atmosphere into the attached biofilm on the portion of the RBC media exposed to the atmosphere. Oxygen enters the bulk liquid by turbulence created from the motion of the rotating disks.
Economic Requirements [7]	
Capex	Medium capital cost.
Opex	Medium Operation Cost. Medium power consumption. Medium technology level.
Downstream Processing and Product Recovery	
Associated Approaches to Product Recovery	For biomass-associated products, biomass is removed from disks e.g. by low shear forces. Product in the supernatant is collected by DSP is similar to traditional, costlier bioprocessing.
Potential Products	A bioproduct associated with the biomass would be ideal.

1. http://dipgra-feder.es/proyectos/images/ecemed/actuaciones/ampliacion-edar/despues.jpg.
2. https://upload.wikimedia.org/wikipedia/commons/3/3c/Rotating_Biological_Contactor.png.
3. Satterfield, CN. (1975). Trickle-bed reactors. *AIChE Journal*, 21(2), 209–228. doi:10.1002/aic.690210202.
4. Grady, CL, Daigger, GT, Love, NG & Filipe, CDM. (2011). Biological Wastewater Treatment (3rd ed.). London: IWA
5. Adav, SS, Lee, D-J, Show, K-Y & Tay, J-H. (2008). Aerobic granular sludge: Recent advances. *Biotechnology Advances*, 26(5), 411-423. doi:10.1016/j.biotechadv.2008.05.002.
6. De Kreuk, M, Krishida, N & Van Loosdrecht, M. (2007). Aerobic granular sludge: State of the art. *Water and Science Technology*, 55(8-9), 75-81.
7. Merwe-Botha, M & Quilling, G. (2012). Drivers for wastewater technology selection assessment of the selection of wastewater treatment technology. Retrieved from http://www.wrc.org.za/Knowledge Hub Documents/Research Reports/TT 543-12.pdf.

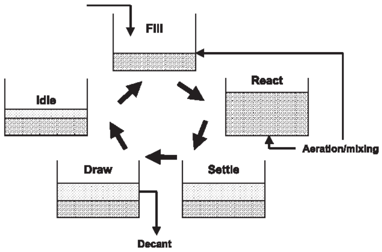
Table 48: Comparison of five bioreactors suitable for WWBRs – TBR

Trickle Bed Reactor	
Diagram	 [1]  [2]

Trickle Bed Reactor	
Description	A typical TBR consists of five major components: the carrier bed, containment structure, wastewater application system, underdrain system and the ventilation system. The carrier bed provides the surface on which the biomass grows. Medium bed materials vary in size, porosity and shape. Plastic (PVC or polypropylene) is typically used as the medium material [3].
When or Why Used in WWTWs	The TBR, also known as the TF, has been used for nearly 100 years to treat municipal and industrial wastewaters aerobically [4, 5, 6]. It is essentially a packed bed biofilm reactor in which the wastewater is trickled over a fixed carrier. Air is counter-currently passed up the media where diffusion between the wastewater and biofilm occurs. The TBRs used in industrial applications include a recycling stream to improve nutrient removal, as well as a liquid-solid separation unit.
Advantages	Well-established and accepted treatment process. Easy to operate. Recycling of the unclarified effluent stream can reinoculate the reactor with biomass producing bacteria. Low pressure drop across bed lowers the power requirements for ventilation. Able to handle low substrate concentrations.
Disadvantages	Clogging of biofilm carrier due to excessive biomass or extracellular polymer growth, or poor pretreatment of influent (presence of particulates). Harvesting of biomass could be difficult because biomass is attached growth and densely packed. Recycling increases pumping duty and operating costs. A continual aeration requirement adds to operating costs
Physical Characteristics	
Reactor Size	Variable, depending on what the treatment objectives are. Water Environment Federation (WEF) reports that the depth of typical TBRs varies from 0.91 m to 6.10 m if roughing is desired [7]. For carbon oxidation, BOD and nitrification, and pure nitrification, the bed depth is typically <12.2 m.
Arrangement/Configuration	TBRs are typically arranged in series, with primary clarifiers before the first stage, and secondary clarifiers after the final stage. Occasionally, intermediate clarifiers are between stages.
Operating Conditions	
Hydraulic Retention Time	It is not possible to determine the biomass concentration within a TBR easily, thereby making it difficult to calculate a sludge retention time or a process-loading factor. Some values for the biomass concentration in a TBR have been reported, but no consensus has been reached on the appropriate manner of calculating this [3]. WEF reports that the total hydraulic load (THL) can be calculated as follows: $THL = \frac{Q_{in} + Q_R}{A} \dots (2)$ where Q_{in} is trickling filter influent, Q_R is recirculation stream A is media specific surface area [7].
Organic Loading	Roughing: 1.5 to 3.5 total organic load (TOL) kg BOD_5 (m^3/day). Carbon oxidation: 0.7 to 1.5 TOL kg BOD_5 (m^3/day). Combined carbon oxidation and nitrification: <1.0 TOL kg BOD_5 (m^3/day) [3].
Effluent Treatment	This depends entirely on the treatment objectives: roughing, carbon oxidation, combined carbon oxidation and nitrification, separate stage nitrification.
Aeration Requirements	Oxygen or air is bubbled into bottom, counter-current to flow of influent.
Economic Requirements [8]	
Capex	Medium capital cost.
Opex	Low operational cost.
Downstream Processing and Product Recovery	
Associated Approaches to Product Recovery	If the product was biomass associated, the removal of the biomass from the media bed would be required. This would require multiple reactors to allow for downtime and removal of the biomass. If the product is loosely associated to the biomass and extracellular, low shear forces will separate it from the biomass. If product is in the bulk liquid, the broth will need to be collected and the DSP will be similar to traditional bioprocessing.
Potential Products	A bioproduct that is associated loosely with the biomass, or extracellular products would be ideal

1. http://www.pallrings.co.uk/wp-content/uploads/2013/06/PR-Brochure_24_Pallpak.pdf.
2. Adapted from http://www.totalwatersolutions.co.za/rotorclear_package_plants.html#tab4.
3. Grady, CL, Daigger, G., Love, NG & Filipe, CDM. (2011). Biological Wastewater Treatment (3rd ed.). London: IWA.
4. Rusten, B, Eikebrokk, B, Ulgenes, Y & Lygren, E. (2006). Design and operations of the Kaldnes moving bed biofilm reactors. *Aquacultural Engineering*, 34(5), 322–331. doi:10.1016/j.aquaeng.2005.04.002.
5. Satterfield, CN. (1975). Trickle-bed reactors. *AIChE Journal*, 21(2), 209–228. doi:10.1002/aic.690210202.
6. Stephenson, T, Simon, J, Jefferson, B & Brindle, K. (2002). Membrane Bioreactors for Wastewater Treatment (p. 62). London: IWA.
7. WEF. (2010). Biofilm Reactors by WEF. McGraw-Hill.
8. Merwe-Botha, M & Quilling, G. (2012). Drivers for wastewater technology selection assessment of the selection of wastewater treatment technology. Retrieved from http://www.wrc.org.za/Knowledge Hub Documents/Research Reports/TT 543-12.pdf.

Table 49: Comparison of five bioreactors suitable for WWBRs – AGSR

Aerobic Granular Sludge in Sequencing Batch Reactor	
Diagram	 [1]  [2]
Description	Dense granules of strong biomass structure, larger than 0.2 mm in diameter, are formed. They are essentially aggregates of microorganisms that are densely packed with a much higher settling rate than the conventional sludge in biological wastewater treatment [3]. From of their unique characteristics, the most desirable attribute is their high biomass retention ability, which allows the smaller reactors with shorter hydraulic residence times thus far. Sequentially operated batch reactors are the only reactor type that has successfully been able to cultivate the granules according to Adav et al. [3]. The reactor is very simple in design and is fed discontinuously, although it can be manipulated to operate under continuous flow conditions.
When or Why Used in WWTWs	Currently, more than 20 large-scale Nereda WWTWs are in operation or under construction. In Wemmershoek and Gansbaai (Western Cape), two large-scale aerobic granular sludge plants using Nereda technology have been successfully implemented to treat a combination of domestic and municipal wastewater. This treatment technology has shown great promise in replacing or using in conjunction with activated sludge systems in WWTWs, to achieve desirable treatment objectives.
Advantages	Strong, dense microbial structures are formed. High biomass retention and settleability. Able to withstand high flow rates and organic loading rates. Uniform and spherical in shape. SBRs can be used as a continuous process. No separate settling tank required, reducing plant footprint. Granules form aerobic and anoxic layers, resulting in COD removal and nitrification and the anoxic layer allows for denitrification to occur. Odour is controlled more effectively by having minimal open areas.
Disadvantages	If incorrect hydraulic retention time (HRT) is employed, washout of fast settling granules will occur. Modifications/improvements required for streams with low COD. Prescreening and filtration to remove suspended solids required. While it is considered 'easy to operate', it is a new technology; so, it is not without its challenges. Plant operators need to be trained in managing unexpected problems.
Physical Characteristics	
Reactor Size	Typical reactor depths vary from 5.5 m to 9 m. The reactors in Gansbaai are 18 m in diameter and 7 m in depth [4]. Morgenroth et al. [5] used an SBR with a volume of 31.4 ℓ and a diameter of 20 cm.
Arrangement/Configuration	Liu and Tay [6] reported that aerobic granules were formed in column-type upflow reactors. The aerobic granular sludge process in Gansbaai uses a three-parallel reactor configuration that increases the flexibility of the plant during the low and peak seasons. This results in operating cost savings in the low seasons when one reactor can be decommissioned. Wemmershoek WWTW uses two 2.5 Mℓ/day reactors in parallel, with each reactor operating at a different stage (feeding, aeration, settling) at any time. Bruin et al. [4] states that the process configuration is flexible, depending on the desired process conditions.
Operating Conditions	
Hydraulic Retention Time	The HRT should be short enough to waste the slow-settling sludge but long enough to achieve the treatment objectives and retain faster settling granules. Liu and Tay [6] found that a short cycle time of four to six hours stimulates microbial activity and production of cell polysaccharides, which in turn favours the formation of granules. These findings would most likely need to be altered for application in WWBRs and large-scale application. Currently, the Wemmershoek WWTW operates at a retention time of four hours.
Organic Loading	Aerobic granules can form across a wide range of organic loading rates from 2.5 to 15 kg/m^3 per day (TOL value).
Effluent Treatment	The five-step sequence of events that occur in an SBR produce effluent that is suitable for environmental discharge [7]. Laboratory studies in an aerobic granular SBRs have shown 90% removal of organic matter and up to 55% ammonia removal [8]. Results from the Gansbaai plant indicated a 93.8% removal in COD, 99% removal in ammonia and 83.5% removal in phosphates [4]. Verbal communication with the plant manager at Wemmershoek also confirmed that those reactors treat the wastewater to environmental standards.
Aeration Requirements	Dissolved oxygen is an important variable and it has been noticed that granules have formed at dissolved oxygen concentrations ranging from 0.7 to >2 mg/ℓ in an SBR. Submerged aeration is used in the Gansbaai aerobic granular sludge process in the form of flat panel diffusers [4]. Fine bubble aeration is used in the Wemmershoek reactors.
Economic Requirements	
Capex	Comparatively speaking, it is difficult to make a direct comparison of this technology to the other technologies used in South Africa since there are only two large-scale operational aerobic granular sludge plants. However, Bruin et al., [4] reported that the technology installed in Gansbaai reported significant reductions in capex and opex. It saves land space since the entire granular activated sludge process takes place within the reactor, including settling. The Nereda technology system set-up in Garmerwolde WWTW in the Netherlands showed a 48% reduction in energy usage [9].
Opex	

Aerobic Granular Sludge in Sequencing Batch Reactor	
Downstream Processing and Product Recovery	
Associated Approaches to Product Recovery	Due to the flocculent nature of the aerated granular sludge, product recovery would be considerably more efficient if the products were intracellular or extracellular and biomass associated. It would merely require the removal of the granules and would improve the DSP time.
Potential Products	Due to the principle of operation of aerobic granular sludge, products associated with the biomass and not in the bulk liquid would improve the ease of DSP. The tendency for the granules to have a high settling rate would improve the efficiency of separating the product and biomass from treated effluent. The production of ɣ-PGA, which is an extracellular, biomass-associated product, is being investigated.

1. Tayana Raper. 2015. Wemmershoek WWTW. Photographed with permission.
2. http://web.deu.edu.tr/atiksu/ana07/02-01.gif.
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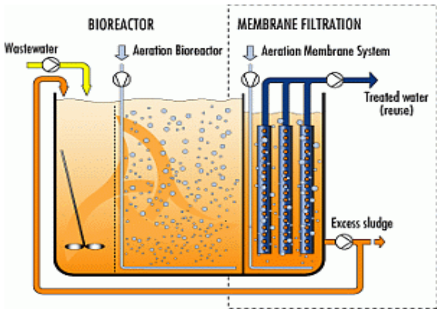
5. Morgenroth, E, Sherden, T, Van Loosdrecht, M, Heijen, J & Wilderer, P. (1997). Aerobic granular sludge in a sequencing batch reactor, 31(12), 3191–3194.
6. Liu, Y & Tay, JH. (2004). State of the art of biogranulation technology for wastewater treatment. *Biotechnology Advances*, *22*(7), 533-563.
7. Grady, CL, Daigger, GT, Love, NG & Filipe, CDM. (2011). Biological Wastewater Treatment (3rd ed.). London: IWA.
8. Mosquera-Correl, A, Vazquez–Padin, J, Arrojo, B, Campos, J & Mendez, R. (2005). Nitrifying granular sludge in a sequencing batch reactor. In Water and Environmental Management Series: Aerobic Granular Sludge (pp. 63-70). London: IWA.
9. Robertson, S, Doutor, J & Van Bentem, A. (2015). Sustainable wastewater treatment using aerobic granular sludge: The Innovative Nereda® Technology. South Africa, Royal HaskoningDHV.

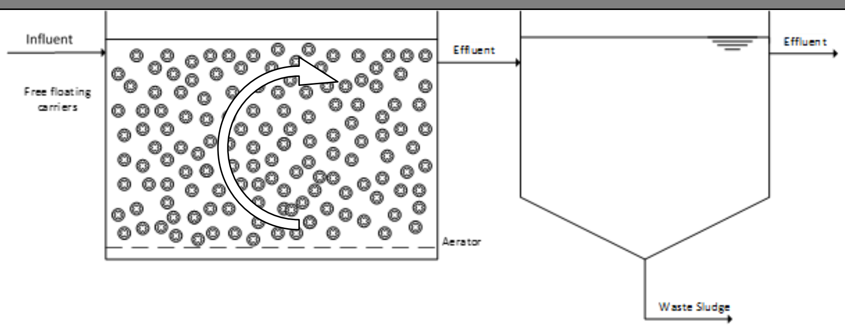
Table 50: Comparison of five bioreactors suitable for WWBRs – MBR

Membrane Bioreactor	
Diagram	 [1]  [2]
Description	Membrane bioreactors can be classified into three types: for separation of and retention of solids; for bubbleless aeration within the bioreactor and for the extraction of pollutants from industrial wastewaters. The membranes are used to separate the biomass and treated effluent and to extract pollutants that are usually difficult to treat using traditional biological wastewater treatment processes [3].
When or Why Used in WWTWs	In the late 1970s, the first commercial scale aerobic MBR process emerged in North America. In South Africa, the equivalent anaerobic process entered the industrial wastewater treatment sector in the 1990s [3]. This technology is increasingly being used to treat wastewater as a key component of water reclamation and reuse systems. It is a variation of the activated sludge process in which a membrane system is used for liquid-solids separation. These reactors are typically used to achieve a high-quality effluent [3]. Illovo Sugar's MBR at Sezela's is a large open tank (4000 m^3) filled with effluent that is aerated from the base of the reactor. There is a bank of flat sheet membranes submerged in the tank through which the treated effluent passes. It was constructed as a 'pilot' plant and was designed to treat a third of the effluent. Practically, it has been found that it can satisfactorily treat 25% of the plant effluent [4].
Advantages	Combined COD, solid and nutrient removal in one unit. Fast start-up. Superior removal of particulate and colloidal matter. Production of high-quality effluent. Excellent for pretreatment if further treatment is required. Reduction of land footprint. High loading rate capability. Capable of treating toxic industrial effluents. [3]
Disadvantages	Replacement of membranes could be costly. High capital cost. Membrane fouling New technology therefore full-scale process requires skilled professionals Does not handle high amounts of non-biodegradable settleable solids and pretreatment is required [3]

Membrane Bioreactor	
Physical Characteristics	
Reactor Size	Average sizes of these reactors could not be found; however, they are usually produced in standard sizes. Various commercial technologies are available. Some of the more well-known include the Kubota process, Zenon Municipal Systems (ZenoGem Process), The ZeeWeed Membrane, Pleide membrane module developed by Orelis & Mitsui Chemicals and there are numerous other listed in [3]. The table below summaries the key design information for one of the first full-scale Kubota MBRs installed in South Africa, at the Illovo Sugar Plant in Sezela, KwaZulu-Natal. [4] Screen: 1.5 mm wedge wire rundown screen Design sludge age: 30 days MBR blower: 2880 Nm^3/hr @ 500 mbar (61.5 kW) FBDA blower: 2 no. Each 7060 Nm^3/hr @ 740 mbar (224 kW) Reactor dimensions: 28 m. 7 m deep. Volume 4310 m^3 Membrane units: 12 no. EK400 Total number of membrane panels: 4800 Membrane type: Kubota Flat Sheet Membrane Panels
Arrangement/Configuration	The number of units required is dependent of the maximum influent flow rate [3]. The Illovo sugar plants use one MBR to reduce the footprint [4].
Operating Conditions	
Hydraulic Retention Time	HRTs are reported for municipal wastewaters to be between 2 and 24 hours in Stephenson et al. [5]. However, they do state that for industrial applications, the HRTs are generally much longer and extend to days rather than hours [3] The Illovo Sugar Plant has a sludge age (HRT) of 30 days. [4]
Organic Loading	Reported organic loading rates of between 0.25 and 16 kg COD/m^3/d.[3]
Effluent Treatment	Stephenson et al. [5] reported removal efficiencies of 90 to 99.8%. It also has a higher performance when compared with that of activated sludge [3]. Illovo Sugar MBR plant has recorded a 95% reduction in COD. [4]
Aeration Requirements	Sezela Plant: Two large blowers supply air via fine bubble diffusers along the floor of the tank. A third smaller blower supplies air as coarse bubbles used to scour and clean the membranes (in all membrane operations regular cleaning is necessary to prevent fouling of the membranes). [4]
Economic Requirements [6]	
Capex	High Capital Cost
Opex	High Operating Cost High Skills requirement
Downstream Processing and Product Recovery	
Associated Approaches to Product Recovery	Cell-associated bioproducts would be removed from the section of the reactor that holds the biomass and influent wastewater. If the product was in the bulk liquid it would need to be determined if it is filtered through the membranes with the effluent, or retained with the biomass by the membranes, to determine the appropriate DSP approach
Potential Products	Products that are easily removed through liquid-solid separation and exploit this inherent principle of operation of the MBR would be ideal

1. Bahrudeen, A. (2014). Rotating biological contactor. Retrieved from http://www.thewatertreatments.com/wastewater-sewage-treatment/rotating-biological-contactor.
2. http://www.lenntech.com/images/mbr_submerged_scheme.jpg.
3. Stensel, HD & Burton, F. (2003). Wastewater Engineering: Treatment and Reuse. New York: McGraw-Hill.
4. Kennedy, S & Young, T. (n.d.). Membrane bioreactors for water reuse in southern Africa. *Water* (p. 62).
5. Stephenson, T, Simon, J, Jefferson, B & Brindle, K. (2002). Membrane Bioreactors for Wastewater Treatment (p. 62). London: IWA.
6. Merwe-Botha, M & Quilling, G. (2012). Drivers for wastewater technology selection assessment of the selection of wastewater treatment technology. Retrieved from http://www.wrc.org.za/Knowledge Hub Documents/Research Reports/TT 543-12.pdf.

Table 51: Comparison of five bioreactors suitable for WWBRs – MBBR

Moving bed Bioreactor	
Diagram	 [1]

Moving bed Bioreactor	
Description	The MBBR process is based on attached growth biofilm principles of wastewater treatment. The core of the process is the biofilm carrier particles. While the biofilm is fixed to the carriers, the medium is thoroughly mixed within a reactor and retained in the reactor. Carrier particle circulation within the bioreactor is provided by the aeration system or by mixers (anaerobic conditions). Biomass and carriers are retained in the bioreactor using effluent screens. Excess biomass sloughs off the carrier particles and passes into the process effluent where it must be separated in a downstream liquid-solids separation system [2].
When or Why Used in WWTWs	MBBR technology is a simple, robust, versatile and compact technology that has become well established in the past two decades. It is used in the wastewater treatment industry to achieve treatment objectives such as BOD removal, nitrification and ammonia oxidation. This technology helps to promote a specialised active biofilm that results in higher efficiencies and a more compact reactor. It is a continuous flow process, independent of the solid separation step due to the retention of active biomass within the reactor [3]. Rusten [4] reported over 400 MBBRs being used for wastewater treatment in 22 different countries.
Advantages	Uses conventional wastewater treatment equipment due to versatility of the technology. A variety of liquid-solids separation approaches can be used. Potentially easy adaptions/modifications to remove biomass. Efficient nutrient removal to environmental specifications. Self-sustaining technology, requiring minimal maintenance. [3]
Disadvantages	Excess biological phosphorous removal not easily accomplished cycling biomass through anaerobic and aerobic zones is necessary for biomass to develop. Requires separate liquid-solids separation step. No filtration capability. Volumetric loadings higher than purely suspended growth systems but lower than other attached growth systems. [3]
Physical Characteristics	
Reactor Size	Due to the simplicity of this technology, the size of the reactor is entirely dependent on the treatment plant where it is being implemented. An MBBR is known to be used to treat process effluent containing phenol.
Arrangement/Configuration	Multiple reactors can be placed in a continuous flow through series arrangement to achieve various treatment objectives such as BOD removal, nitrification and denitrification, with each reactor designated to a specific treatment [3].
Operating Conditions	
Hydraulic Retention Time	HRT is dependent on the desired treatment objective. An example of one applied in a South African municipality was not found. $SRT = \left(\frac{VX}{Q_w X_w + Q X_e}\right)$ V is reactor volume (ℓ); X is the average biomass concentration (mg VSS/ℓ), Q_w is the excess sludge (L/d); X_w is the concentration of the excel sludge (mg VSS/ℓ); Q is the wastewater flow rate (ℓ/d) and X_e is the effluent concentration (mg VSS/ℓ) [5].
Organic Loading	The surface area organic loading depends on whether the MBBR is being used for high, normal or low rate treatment objectives: High Rate: >20 g/m^{2}d Normal Rate: 5 to 15 g/m^{2}d Low Rate: 5 g/m^{2}d [3]
Effluent Treatment	The level of treatment is dependent on the loading rate: High Rate: 75 to 80% removal of BOD. Normal Rate: 80 to 90% removal of BOD. Low Rate: preceding nitrification. [3]
Aeration Requirements	Air is bubbled with a coarse bubbler into the reactor to help with suspension of the carriers and oxygen transfer.
Economic Requirements	
Capex	There was no data in the WRC report resource for the MBBR, which was used for the other reactors.
Opex	
Downstream Processing and Product Recovery	
Associated Approaches to Product Recovery	In this situation, a solid-liquid separation step would be required regardless of whether the bioproduct is in the medium or biomass associated, merely due to the nature of operation of this bioreactor.
Potential Products	Products that are easily removed through liquid-solid separation and exploit this inherent principle of operation of the MBR would be ideal. The production of ɣ-PGA, which is an extracellular, biomass-associated product, is being investigated.

1. Adapted from Grady, CL, Daigger, GT, Love, NG & Filipe, CDM. (2011). Biological Wastewater Treatment (3rd ed.). London: IWA.
2. Grady, CL, Daigger, GT, Love, NG & Filipe, CDM. (2011). Biological Wastewater Treatment (3rd ed.). London: IWA.
3. Stephenson, T, Simon, J, Jefferson, B & Brindle, K. (2002). Membrane Bioreactors for Wastewater Treatment (p. 62). London: IWA.
4. Rusten, B, Eikebrokk, B, Ulgenes, Y & Lygren, E. (2006). Design and operations of the Kaldnes moving bed biofilm reactors. *Aquacultural Engineering*, 34(5), 322–331. doi:10.1016/j.aquaeng.2005.04.002.
5. Ahmadi, M, Izanloo, H, Mehr, A, Amiri, H & Sepehr, MN. (2011). Upgrading of Kish Island Markazi wastewater treatment plant by MBBR. *Journal of Water Reuse and Desalination* (Vol. 1, p. 243). doi:10.2166/wrd.2011.038.

6.4 Final Selection of Bioreactors for WWBR

6.4.1 Refinement of the key criteria for selection

To select suitable bioreactors from Section 6.3, the criteria has to be prioritised. Table 52 represents this prioritisation by analysing each of the selection criteria critically and identifying whether it satisfies the two key requirements, based on the definition of a WWBR:

- Produce a product in a different phase that is easily removed and separated from the substrate and biomass to decrease the load on the DSP through the inherent bioreactor design.
- Decouple hydraulic and solid residence times.

Table 52: Bioreactor design requirements in order of priority

	#	Requirement
Design Priority	1	Decouples hydraulic and solid retention times
	2	Continuous or semi-continuous (cannot store flows)
	3	Product formation in different phase
	4	Bioreactor design facilitates the recovery of the product
Operational Priority	5	Think big! Commodity rather than niche
	6	Influences microbial community, non-sterile
	7	Gives advantage to product: creates ecological niche
	8	Water released into environment eventually

The first four requirements have been labelled as ‘Design Priority’. Requirement 4 is a combination of two requirements in Table 45: Requirement 8, “Can product be recovered?” and Requirement 9, “Bioreactor design conducive to reducing DSP load?” These two points have been combined since the recovery of the product is a function of how the biofilm grows and attaches in the bioreactor and whether the bioreactor design facilitates this attachment process. This in turn affects how the product is removed and whether additional process units are required to separate product from the bulk liquid. If a bioreactor is unable to fulfil **all** four design priorities, then it is unlikely that it will be able to produce the desired bioproduct in a quantity and phase that makes the process economically feasible.

The other four categories have been labelled as “Operational Priority”. This set of criteria refers to factors that are independent of the design and pertain to important operational factors of a WWBR that ensure its success. Should a bioreactor technology fail to comply with the “design priority” criteria, in spite of fulfilling the “operational priority” criteria, it remains unsuitable for the use in WWBR applications.

The desired goal for these WWBRs is to incorporate the bioreactors into existing wastewater treatment plants. Thus, it is critical that they are able to handle continuous or semi-continuous flows that have seasonal variations in flow rates and composition. WWTWs cannot ‘shut down’ owing to the continuous flow of wastewater generated by industry and the population.

6.4.2 Criteria fulfilment of the selected bioreactors

In order to adequately justify the selection of three bioreactors for further study, Table 53 has been compiled for each of the five bioreactors outlined in Section 6.3 to show the degree to which the bioreactors fulfil the criteria outlined in Table 52.

The following scale will be used to show the extent to which the bioreactors satisfy the requirements:

Completely Complies	Mostly Complies	Marginally Complies	Does Not Comply
+++	++	±	x

Table 53: Composite table showing the degree to which the five bioreactor categories fulfil the selection criteria

	Criteria		Aerobic granular sludge in an SBR	Rotating Biological Contactor	Membrane Bioreactor	Moving Bed Biofilm Reactor	TBR
Most Important	1	Decouples hydraulic and solid retention times	+++	+++	+++	+++	+++
	2	Continuous or semi-continuous (cannot store flows)	++	+++	++	+++	++
	3	Product formation in different phase	+++	+++	++	+++	+++
	4	Reactor design facilitates the recovery of the product	+++	++	±	+++	x
Least Important	5	Think big! Commodity rather than niche	++	+++	++	+++	+++
	6	Influences microbial community, non-sterile	+++	++	++	+++	++
	7	Gives advantage to product: creates ecological niche	+++	++	++	+++	++
	8	Water released into environment eventually	+++	++	+++	++	++
Number of criteria that completely complies			6	4	2	7	3

From Table 53 it is evident that the reactor types that fulfil the critical requirements are (in order of best compliance): MBBR, aerobic granular sludge in a sequencing batch reactor (AGS-SBR) and the RBC. The main reasons behind this analysis are outlined in the SWOT analysis in Section 6.4.3.

The TBR did not fulfil criterion number 4 due to the process downtime that would be required to remove the packed material, separate the biomass and product and start the treatment procedure. This would require storing wastewater flows, or having multiple bioreactors, and re-establishing equilibrium in the system. Clogging is a known problem in TBRs used in regular wastewater treatment, resulting in channelling and poor treatment efficiencies (Antonie, 1976). Clogging may be aggravated with product formation, especially if the product is extracellular.

The MBR also fell short in category number 4. While it is a continuous system, the membranes require replacement and maintenance to prevent clogging. MBRs have also not yet been applied at full municipal scale. They have high capex and opex and require skilled plant technicians. In the context of South Africa's existing WWTWs, this presents an additional obstacle (Henze, et al., 2002; Grady, et al., 2011).

6.4.3 SWOT analysis of the three reactors selected for use in WWBRs

For the purpose of this comparison, the SWOT analysis has been based on the ability of each of the outlined bioreactors to fulfil the top criteria that were outlined in Section 6.4.1. The following questions were asked when performing the SWOT analysis on these bioreactors:

Strengths: What characteristics of the bioreactor technology allow it to fulfil the requirements and render it suitable for applications in WWBRs?

Weaknesses: What are the major drawbacks about this technology, concerning process operation and treatment objectives?

Opportunities: Is there potential for retrofitting and adaption to South Africa's current wastewater treatment plants and infrastructure?

Threats: Does the bioreactor technology have risks associated with its operation, and implementation?

Table 54: SWOT analysis of selected bioreactors

RBC	MBBR	AGS-SBR
Strengths		
• Mechanically simple and reliable process. • Large-scale applications used successfully worldwide. • Inherent aeration by nature of shaft rotation. • Recycling loops are not required due to continued microbial growth and thus water treatment. • Does not require very skilled operators. • Able to handle lower substrate concentrations. • Creates a microbial niche – organisms present in the wastewater naturally adhere to the disks. • Rotating disks agitated the mixed liquor keeping sloughed biomass in suspension and well mixed at each stage of treatment. • Not affected by shock variations in hydraulic and organic loading.	• Versatile technology allowing creative solutions. • Active biomass is retained in the reactor continuously. • The suspended carriers promote the formation of active biomass, resulting in higher efficiencies and process stability. • Continuous flow process. • Multiple stages can be achieved through arrangement in series, without the need to pumping (similar to activated sludge process). • Density of carriers close to water, thus minimising mixing energy required to keep them in suspension. • Does not require skilled operators. • Simple aeration grid designed on base of reactor eliminates the need for diffuser replacements and maintenance.	• Hydraulic load variations are readily handled by for aerobic granular sludge systems. • High biomass retention. • SBRs can be used as a continuous process. • Does not require additional clarifiers downstream. • Obtains high treatment efficiencies at low oxygen saturation concentrations (De Kreuk, et al., 2005; Verster, et al., 2013). • Granules have a fast settling rate. • Recycles and mixers are not required saving on energy costs and maintenance. • Land footprint of aerobic granular sludge is significantly decreased compared to other technologies.
Weaknesses		
• Requires primary clarification and pretreatment as it does not handle particulate matter well. • If insufficient wetting of the biomass occurs, it leaves the disks vulnerable to nuisance organisms such as algae and worms. • Development of uneven biofilm growth.	• Good screening and grit removal is required to prevent build-up of inert material. • Foaming is known to occasionally form at start-up. Antifoam added into the process can cause decreased diffusion to the biofilm.	• Aerobic granular sludge formed by slow-growing bacteria is more stable than when fast-growing bacteria are present. • Competency of operators running a relatively new technology at a large scale. • Requires pretreatment to remove solids.
Opportunities		
• Modifications to the reactor design could be incorporated to continuously remove surface biomass for product harvesting.	• Great potential for modifications to the design to facilitate easy liquid-solid separations. • Versatility makes MBBRs suitable for retrofit installation into existing tanks. In South Africa, the predominant technology is activated sludge. MBBRs could be fitted into these existing tanks.	• Successful large-scale application of aerobic granular sludge in an SBR in Gansbaai and Wemmershoek have been implemented and showed excellent treatment efficiencies. This shows great promise for this technology on a large scale.
Threats		
• Temperatures below 12°C in colder seasons will result in decreased efficiency. • Enclosures are often needed around the RBCs to minimise effects of sunlight, nuisance organisms and temperature fluctuations. These enclosures require odour control and often heat control to avoid condensation and corrosion of the units. • Process failures due to inadequate designs of the shaft system.	• Too much sloughing in the reactor could cause the biomass to flow out with the media, and prevent water treatment and product formation.	• Process is unstable as washout can easily occur. • Technology is not well understood on a large-scale application. • Effects of a biopolymer forming microorganism on a granular formation are not well understood.
References		
(Adav, et al., 2008; Antonie, 1976; Grady, et al., 2011; Stensel & Burton, 2003; WEF, 2010)	(Borghei & Hosseini, 2002; Grady, et al., 2011; Henze, et al., 2008; WEF, 2010)	(De Kreuk, et al., 2005; Gademan, et al., 2010; Henze, et al., 2002; Verster, et al., 2013)

Experimental studies must be conducted to further assess the viability of these technologies, and to compare the actual performance of the three. To this end, a laboratory-scale MBBR and AGS-SBR have been built and commissioned to produce the PGA polymer that was selected in Section 5.4.2 as a suitable candidate product for the biological reactor. This is an ongoing project and results to date are reported in Appendix E. This study should ultimately contribute to the ability to select the most suitable bacterial bioreactor for different WWBR systems.

6.5 Bioreactor Selection for the Integrated WWBR

The design of bioreactors suitable for use with a wastewater feedstock poses specific challenges, as does the placement of the bioreactor within the greater whole of the biorefinery. The factors involved have been considered regarding the bacterial reactor (Section 6.1). The approach taken in this study is applicable to the selection of the other bioreactors within the WWBR and can be used as the starting point for initial choices. Once the options have been reviewed and a shortlist created, the process developed in this chapter can be applied using the key criteria and SWOT analysis to make a final selection. However, the process may yield two or three potential candidate bioreactor configurations, which should then be assessed experimentally.

Incorporation of the system developed here into the conceptualisation of WWBRs in South Africa, or its use for a particular WWBR design, is explored further in Chapter 9.

7 GENERIC FLOWSHEETS AND MASS BALANCES FOR WWBR DESIGN

This study has recognised the need for multiple unit operations to be included in the WWBR flowsheet to allow multiple specifications to be met, namely, harvesting and beneficiating different components of the wastewater and meeting the requisite water quality. This requires the maximising of conversion to product and maximising of quality of product water to be separated. In the preceding project run by CeBER (Verster, et al., 2014), this approach was recognised by compiling a generalised flowsheet, given in Chapter 2, Figure 2.

Wastewater treatment generally consists of settling, primary treatment, secondary treatment and possibly polishing steps. It is expected that a WWBR will include similar stages to produce water compliant to the specified quality as one of the products of defined quality. The optimisation of each unit operation is required with respect to its yield, efficiency, and product quality. Furthermore, the optimisation of the integrated process is required to maximise the overall product outputs and to ensure compliance with respect to water quality. In this section, key features of the WWBR flowsheet mass balances are considered.

7.1 Approach to Flowsheet Development for Biorefineries

Each biorefinery case study results in a unique process flowsheet; however, these encompass common building blocks including unit operations focused on removing solids, converting the soluble organic carbon component, using nitrogen and phosphorous, removing trace contaminants and delivering required water quality. Some unit operations may serve more than one purpose. The flowsheet development is guided by heuristic assumptions that make a first-order feasibility analysis possible and contribute to understanding the potential of the biorefinery. These are discussed in more detail in the validation study in Chapter 8.

7.1.1 An overview flowsheet for WWBRs

An overview flowsheet for a generalised WWBR is presented in Figure 21, with its accompanying lists of unit operations and process streams presented in Table 55 and Table 56. The mass balance equations for this flowsheet are given in Section 7.1.2.

The generic WWBR uses one or more wastewater streams (A1-4) as feedstock to produce products, including compliant water. More than one wastewater inflow may be used, either simply because these are the streams that need remediation, or because the streams complement each other in terms of nutrients available for product formation.

The combined feedstock is separated into a solids stream (U1) and a raw wastewater stream (B1). The latter is treated in a series of bioreactors, using the diversity of functions offered by varying the focus in each reactor. The bacterial reactor (1), algal reactor (2) and macrophyte reactor (3) each improve the quality of water, with the separated effluent of the prior reactor becoming the influent (D1 and F1) of the next, and the solution separated from the final effluent completely compliant “water as product” (Z).

Each reactor also produces one or more value-added products (V, W & X), which are separated for further processing, as well as a solids slurry (U2, U3, U4 and U5), which is combined with the feedstock solids. This combined slurry forms the influent to the solids reactor (4), which is likely to be a fungal reactor. The solids reactor produces products (Y), including the final “catch-all” compost. Each of the four bioreactors may need one or more supplement streams (B2-4, D3-5, F2-4 and U6-8) for optimal functioning. Each reactor also has carbon dioxide (photosynthesis and respiration) and water (precipitation and evaporation) flows, each forming either a nett inflow or a nett outflow. The generic flow diagram allows provision for a biomass recycle (C4) in the bacterial reactor and a feedstock bypass (D2) to the algal reactor which may be used to achieve optimal performance.

A more detailed version of the flow diagram for the generalised WWBR is split into flowsheets for each reactor train. These flowsheets area presented in Sections 7.4 and 7.5 with the equations for the relevant mass balance.

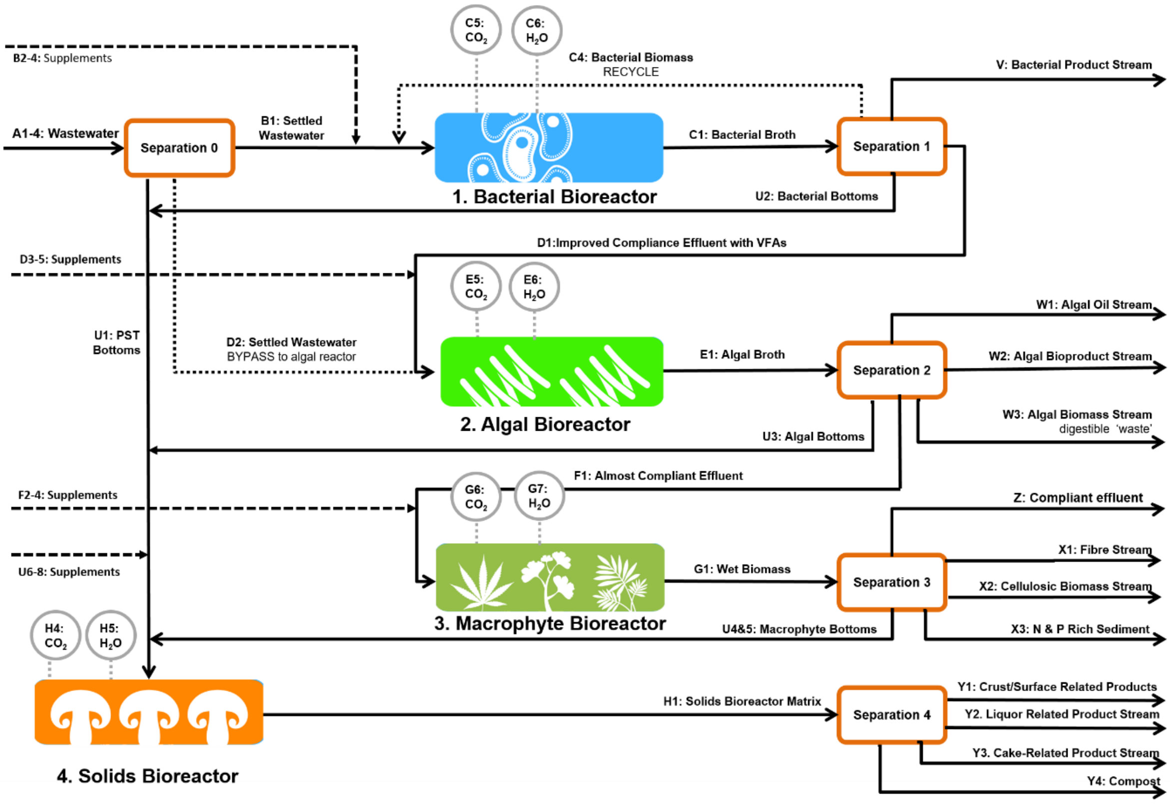


Figure 21: Generic WWBR overview flowsheet (see Table 55 and Table 56)

Table 55: Overview of operations in unit groups for a generic WWBR (see Figure 21)

Unit Group Numbers	Type	Unit Group Description
0.1-0.2	Separation 0	Separation of raw influent streams, with primary settling and splitting.
1.1	Bioreactor	Bacterial bioreactor, preceded by a holding/mixing tank.
1.2-1.4	Separation 1	Separation of bacterial product, bacterial biomass and improved effluent (to algal reactor).
2.1	Bioreactor	Algal bioreactor, preceded by a holding/mixing tank.
2.2-2.5	Separation 2	Separation of algal products, algal biomass and almost-compliant effluent (to macrophyte reactor).
3.1	Bioreactor	Macrophyte bioreactor, preceded by a holding/mixing tank.
3.2-3.6	Separation 3	Separation of fibre, cellulosic biomass, sediment and compliant effluent (leaving system) some processes seasonal.
4.1	Bioreactor	Solids reactor, preceded by a holding/mixing tank.
4.2-4.4	Separation 4	Separation of solids reactor product, separated into crust-associated products, liquor-associated products and cake-associated products, the remainder being compost.

Table 56: Overview of streams for a generic WWBR (see Figure 21)

Stream Number	Stream Description	Relation to Process Units	Relation to Other Streams (equations refer to mass balance, not volume)
A1-A4	Raw wastewater	Into Separation 0 (Units 0.1-0.2-3)	Mixed incoming stream
B1	Settled raw wastewater	From Separation 0 Into Unit 1: Bacterial Bioreactor	B1 = [A1-4] − U1 − D2 Composition same as D2
B2-4	Supplementary feed	Into Unit 1: Bacterial Bioreactor	Determined by process needs
C1	Bacterial broth	From Unit 1: Bacterial Bioreactor Into Separation 1	C1 = B1 + [B2-4] + C4 + C5 + C6 Composition changed from B1 including increased VFA content
C4	Bacterial biomass recycle	From Separation 1 Into Unit 1: Bacterial bioreactor	C4 = C1 − U2 − D1 − V1 Composition changed from C1 Low liquid content
C5	CO_2	From Unit 1: Bacterial Bioreactor To atmosphere	CO_2 only
C6	H_2O	Between Unit 1: Bacterial Bioreactor and atmosphere	H_2O only, rainfall and/or evaporation
D1	Improved compliance effluent with VFA content	From Separation 1 Into Unit 2: Algal Bioreactor	D1 = C1 − C4 − U2 − V1 Composition similar to dissolved composition C1
D2	Settled raw wastewater, bypass stream	From Separation 1 Into Unit 2: Algal Bioreactor	D2 = [A1-4] − B1 − U1 Composition same as B1.
D3-5	Supplementary feed	Into Unit 2: Algal Bioreactor	Determined by process needs
E1	Algal broth	From Unit 2: Algal Bioreactor Into Separation 2	E1 = D1 +D2 + [D3-5] + E5 + E6 Composition changed from D
E5	CO_2	From atmosphere Into Unit 2: Algal Bioreactor	CO_2 only
E6	H_2O	Between Unit 2: Algal Bioreactor and atmosphere	H_2O only, rainfall and/or evaporation
F1	Almost-compliant effluent	From Separation 2 Into Unit 3: Macrophyte Bioreactor	F1 = E1 − W1 − W2 − W3 − U3 Composition same as dissolved composition E1
F2-4	Supplementary feed	Into Unit 3: Macrophyte Bioreactor	Determined by process needs
G1	Wet macrophyte biomass	From Unit 3: Macrophyte Bioreactor Into Separation 3	G1 = F1 + [F2-4] + G6 + G7 Composition changed from F1 Combination of liquid, fibre and sediment
G6	CO_2	From atmosphere Into Unit 3: Macrophyte Bioreactor	CO_2 only
G7	H_2O	Between Unit 3: Macrophyte Bioreactor and Atmosphere	H_2O only, Precipitation/Evaporation
H1	Solids matrix	From Unit 4: Solids Reactor Into Separation 4	H1 = U1 + U2 + U3 + U4-5 + [U6-8] − H4 + H5 Composition complex.
H4	CO_2	From Unit 4: Solids Reactor To atmosphere	CO_2 only
H5	H_2O	Between Unit 4: Solids Bioreactor and Atmosphere	H_2O only, Precipitation/Evaporation
U1	Primary settling tank bottoms	From Separation 0 Into Unit 4: Solids Reactor	Volume and composition dependent on incoming streams. U1 = [A1-4] − B1 − D2 Dependent on primary settling tank (PST) efficiency
U2	Bacterial bottoms	From Separation 1 Into Unit 4: Solids Reactor	U2 = C1 − (D1 + I + C4) Composition based on bacterial biomass
U3	Algal biomass not to product streams	From Separation 2 Into Unit 4: Solids Reactor	Total algal biomass = U3 + L U3 = E1 − (F1 + W1 + W2 + W3) Composition based on algal biomass
U4-5	Cellulosic biomass and nitrogen- and phosphorous-rich sediment	From Separation 3 Into Unit 4: Solids Reactor	U4 + U5 = G1 − (Z + X1 + X2 + X3) U4: Composition based on macrophyte (above ground) biomass U5: Composition based on sediment accumulation (not directly related to input streams), composition the same as X3
U6-8	Supplementary feed	Into Unit 4: Solids Reactor	Determined by process needs
V1	Bacterial product stream	From Separation 1 Exit system	V1 = (B1 + [B2-4]) × (Bacterial bioproduct yield coefficient) Stream needs further processing for pure product

Stream Number	Stream Description	Relation to Process Units	Relation to Other Streams (equations refer to mass balance, not volume)
W1	Algal oil stream	From Separation 2 Exit system	W1 = (D1 + D2 + [D3-5] + E5) × (Algal oil yield coefficient) Stream needs further processing for pure product
W2	Algal bioproduct stream	From Separation 2 Exit system	W2 = (D1 + D2 + [D3-5] + E5) × (Algal bioproduct yield coefficient) Stream needs further processing for pure product
W3	Algal biomass (digestible 'waste')	From Separation 2 Exit system	W3 = (D1 + D2 + [D3-5] + E5) − (W1 + W2 + F1) Note U3 can be 0 Composition same as U3
X1	Fibre stream	From Separation 3 Exit system	X1 = G1 × (1 − moisture content fraction) × (Fibre compositional fraction)
X2	Cellulosic biomass stream	From Separation 3 Into further processing and/or leave system	X2 = G1 × (1 − moisture content fraction) × (Cellulosic compositional fraction)
X3	Nitrogen- and phosphorous-rich sediment	From Separation 3 Exit system	Composition based on sediment accumulation (not directly related to input streams)
Y1	Crust/surface product stream	From Separation 4 Exit system	Y1 = (U1 + U2 + U3 + [U4-5] + [U6-8]) × (Crust product yield coefficient)
Y2	Liquor-associated product stream	Separation 4 Exit system	Y2 = (U1 + U2 + U3 + [U4-5] + [U6-8]) × (Liquor-associated product yield coefficient)
Y3	Cake-related product stream	Separation 4 Exit system	Y3 = (U1 + U2 + U3 + [U4-5] + [U6-8]) × (Cake-related product yield)
Y4	Compost	Separation 5 Exit system	Y4 = H1 − (Y1 + Y2 + Y3)
Z	Compliant effluent	From Separation 4 Exit system	Composition must comply with discharge standards (either for discharge into natural water body or for irrigation or for reuse)

7.1.2 Mass balance equations for overview flowsheet

The generalised flow diagram gives a simplified view of the WWBR and allows for an overall mass balance to be constructed. (The approach to mass balances for the detailed flowsheets for the four bioreactor trains is given in Section 7.3.) In the mass balance, the following applies:

It is considered as a continuous system, with an assumption of no accumulation over the time interval of analysis. For some sections of the process, this means that the mass balance must be calculated over a relatively long time period and averaged to the per day basis. In this model, a year was used. In particular, aspects of the macrophyte bioreactor train will operate on an annual cycle. Thus, the overall mass balance is considered to have zero accumulation over a full year.

The symbol for each stream represents the combined value of concentration (C) multiplied by the flow rate (Q).

For each process portion (separation or reactor), components with overall negative signs are nett outflows and positive components are nett inflows. The CO_2 uptake or respiration rates (streams C5, E5, G6 and H4), and rain or evaporation streams (C6, E6, G7 and H5) are assigned a positive sign by default, because their nett value could be an in- or outflow depending on-site specific factors, including the wastewater concentration and the geographic location. Should these streams actually be outflows, their stream flow rate is quantified as less than zero. The yield coefficients then determine the final sign, for example positive (inflow) for photosynthetic carbon uptake, negative (outflow) for respiration, positive for rainfall and negative for evaporation.

Table 57: Mass balance equations for the overview flowsheet

Type	Overall Mass Balance
Separation 0	[A1-4] − (B1 + D2 + U1) = 0
1. Bacterial Bioreactor	(B1 + [B2-4] + C4 + C5 + C6) − (C1) = 0
Separation 1	(C1) − (C4 + D1 + V1 + U2) = 0
2. Algal Bioreactor	(D1+ D2 + [D3-5] + E5 + E6) − (E1) = 0
Separation 2	(E1) − (F1 + W1 + W2 + W3 + U3) = 0
3. Macrophyte Bioreactor	(F1 + [F2-4] + G6 + G7) − (G1) = 0
Separation 3	(G1) − (Z + X1 + X2 + X3 + [U4-5]) = 0
4. Solids Bioreactor	(U1 + U2 + U3 + [U4-5] + [U6-8] + H4 + H5) − (H1) =0
Separation 4	(H1) − (Y1 + Y2 + Y3 + Y4) = 0

7.2 A Note on the Energy Balance for a Wastewater Biorefinery

Most existing biorefineries are primarily aimed at producing energy (Ghatak, 2011) or biomass-for-energy production, whereas the third-generation biorefinery focuses on higher value products and only considers energy as a final use of the remaining chemical potential, once maximum value has been extracted for other uses (Sections 2.2 and 2.3). This generic WWBR does not specifically include an energy production unit, although there is potential focusing on biofuel or bioenergy production in each of the three reactors or to add an additional bioenergy unit. The focus on energy as a primary product is an area of significant distinction between conventional biorefinery thinking and the third-generation biorefinery in general, and the WWBR in particular.

The exclusion of an energy production unit is also a response to the fact that there are several different scenarios regarding the placement of an energy recovery unit. One of these is to use the algal biomass product stream for anaerobic digestion on-site (Inglesby, et al., 2015; Olguín, 2012). Alternatively, anaerobic digestion can be used as pretreatment for the solids reactor, and a potential compliance step before the final composting (Ferry & Giljova, 2015). In either case, the fuel can be used to heat the bacterial bioreactor to increase the reaction rates, to heat the anaerobic digester itself, to produce electric power for other energy needs or a combination of these. Moreover, there is the possibility of creating a microbial fuel cell using one of the streams in the WWBR (Cerrillo, et al., 2016). Further, most energy savings are involved in plant design and layout, with smart co-location of units and their connecting pipes, using pinch technology to cascade (Isafiade, et al., 2015). For these reasons, the scope of this model has been limited to material flows.

Several factors are important to note before analysing WWBRs. Firstly, WWBRs work with waste streams that are not sterilised; therefore, the energy cost associated with sterilisation can be omitted, or reduced to a maintenance cleaning role (Mooij, et al., 2015; Verster, et al., 2014). Since wastewater streams are usually more dilute than other feedstocks, energy requirements per mass of nutrient for pumping may be higher (Ekama, et al., 2011). The required energy density of the units should be assessed, to determine the feasibility of using renewable energy sources where appropriate. In particular, the potential for energy production from “residual” streams within the WWBR should be included (Ghatak, 2011).

7.3 Approach to Mass Balances for Detailed Flowsheets of Bioreactor Trains

The first step in analysing a process flowsheet is to construct material and energy balances. This can inform techno-economic feasibility as well as environmental performance. To close the material and energy balances, the likely conversions, yields and efficiencies of the unit processes must be estimated. This is a work in progress focused on material balances only to describe material flows. Estimates used in a study substantiating the mass balances for a bacterial bioreactor are explained in Section 8.2 followed by a demonstration of mass balances for an integrated WWBR (Section 8.3). These are explored further in the possible scenarios presented in Sections 8.3, 8.4.2 and 8.4.3.

7.3.1 The approach to the mass balances

A lead commercial product is selected for each biorefinery case to suit the wastewater and the surrounding market. In addition to the lead product being well suited to manufacture from the particular wastewater, a market analysis establishing the local needs and demand for products contributes to the choice of lead product. Further to this, production of water quality compliant with specifications is a prerequisite. All other products produced from the wastewater are secondary. If, for example, the main product is an algal product, the entire bacterial reactor can be considered a pretreatment to produce VFAs or liberate nitrogen and phosphorous to supplement the algal process. In this way, the unit processes are optimised for one commercial product and water while, as secondary priority, the robustness of the system is considered. A selection of case studies illustrating this approach are presented in Chapter 8.

In this chapter, a preliminary set of material balances is presented for the bacterial bioreactor (Section 7.4). Similar material balances have been constructed for each of the other bioreactors, and are included in Appendix F, with only the bacterial reactor unit presented in this chapter.

7.3.2 General symbol conventions

C-inflow: The amount of carbon in the inflow streams, excluding CO_2 uptake (see Section 7.3.3), available to be converted into biomass, product or CO_2, used as basis for calculations. Where CO_2 is used, it is recorded as a separate entity and added to carbon inflow for the mass balance.

C-product: The amount of carbon in the product, used as basis for calculations.

Q_{STREAM} = Volumetric flow rate of the specified stream (m^3/day)

$C_{S(STREAM)}$ = Concentration of element in the specified stream (C = Concentration, $_{S}$ = $_{C,N,P}$)

$C_{C(STREAM)}$ = soluble carbon (kg/m^3) in stream

$C_{N(STREAM)}$ = soluble nitrogen (kg/m^3) in stream

$C_{P(STREAM)}$ = soluble phosphorous (kg/m^3) in stream

$N_{S(STREAM)}$ = Total constituent in specified stream (kg/day) (N = Total amount in kg/day, $_{S}$ = $_{C,N,P,W}$)

$N_{C(STREAM)}$ = Total carbon in specified stream (kg/day)

$N_{N(STREAM)}$ = Total nitrogen in specified stream (kg/day)

$N_{P(STREAM)}$ = Total phosphorous in specified stream (kg/day)

$N_{W(STREAM)}$ = Total water in specified stream (kg/day)

In any given stream, N = IN + X + P, namely, the stream flow rate is the sum of the residual unconverted component from the inflow, biomass component and the product component(s).

$X_{React,S(STREAM)}$ = Biomass fraction from specified reactor in specified stream (kg/day)
(X = biomass, $_{React}$ = $_{Reactor}$, $_{S}$ = $_{C,N,P}$)

$X_{React,C(STREAM)}$ = Carbon in biomass fraction of specified stream (kg/day)

$X_{React,N(STREAM)}$ = Nitrogen in biomass fraction of specified stream (kg/day)

$X_{React,P(STREAM)}$ = Phosphorous in biomass fraction of specified stream (kg/day)

$P_{i,S(STREAM)}$ = Product i fraction of specified stream (kg/day) ('i' is specified in terms of exiting product stream, e.g. X1, Y2, W3…, $_{S}$ = $_{C,N,P}$)

$P_{i,C(STREAM)}$ = Carbon in Product i fraction of specified stream (kg/day)

$P_{i,N(STREAM)}$ = Nitrogen in Product i fraction of specified stream (kg/day)

$P_{i,P(STREAM)}$ = Phosphorus in Product i fraction of specified stream (kg/day)

$IN_{S(STREAM)}$ = Unconverted inflow component, in specified stream (kg/day) (IN = inflow component, $_{S}$ = $_{C,N,P,W}$).

Inflow component may consist of unconverted substrate, biomass or product, entering the specified reactor unit, and available to biological conversion.

$IN_{C(STREAM)}$ = Carbon in unconverted inflow component fraction of specified stream (kg/day)

$IN_{N(STREAM)}$ = Nitrogen in unconverted inflow component fraction of specified stream (kg/day)

$IN_{P(STREAM)}$ = Phosphorous in unconverted inflow component fraction of specified stream (kg/day)

$F_{N/C,component}$ = ratio of nitrogen to carbon in the specified component.

For example, the $F_{N/C,XBact}$ is the ratio of nitrogen to carbon in the bacterial biomass (wt% N)/(wt% C), which is 0.049/0.487 or 0.101 g-N/g-C using default model values provided by Wu (2015). The set of values, $F_{N/C,Xreact}$, $F_{N/C,INreact}$, and$F_{N/C,PXi}$ link the carbon and nitrogen balances.

$F_{P/C,component}$ = Ratio of phosphorous to carbon in the specified component.

For example, the $F_{P/C,XBact}$ is the ratio of phosphorus to carbon in the bacterial biomass (wt% P)/(wt% C), which is 0.025/0.487 or 0.051 g-P/g-C using default model values from Wu (2015). This set of values ($F_{P/C,Xreact}$, $F_{P/C,INreact}$, $F_{P/C,PXi}$) link the carbon and phosphorous balances.

SC = fraction of solids in suspension = (mass of solids)/(mass of total sludge)

7.3.3 Reactor conversion value conventions for carbon mass balance and associated assumptions

The reactor conversion values used to describe the bacterial reactor (Bioreactor 1) are set out in Table 58. In this study, these have been defined on an elemental basis and are presented in terms of carbon here. The yields commonly found in literature are calculated on the full mass of product (full composition, including e.g. carbon, hydrogen, oxygen, nitrogen, phosphorous) per mass of substrate used (full composition, including e.g. carbon, hydrogen, oxygen, nitrogen, phosphorous), and are therefore converted to the C-specific values to comply with a carbon mass balance used here. A similar approach can be taken for the nitrogen and phosphorous balances.

The yield for carbon dioxide is only relevant for the carbon mass balance, and not relevant for the nitrogen or phosphorous mass balances. Literature values may refer to CO_2 yield per biomass concentration. In this project, the biomass yield per C-inflow has been combined with the CO_2 yield per biomass concentration, to give a stoichiometric CO_2 yield per C-inflow.

Table 58: Carbon mass balance yield factors

Conversion description	Unit	Symbol of factor
Mass of carbon reporting to biomass as a fraction of that present in influent stream to reactor	kg C(reactor biomass)/kg C(inflow to reactor)	$Y_{C,X/IN}$
Mass of carbon reporting to product as a fraction of that present in influent stream to reactor	kg C(product)/kg C(inflow to reactor)	$Y_{C,Pi/IN}$
Mass of carbon entering or leaving as CO_2 as a fraction of that present in influent stream to reactor	kg C(CO_2)/kg C(inflow to reactor)	$Y_{C,CO2/IN}$
Mass of carbon remaining unconverted as a fraction of that present in influent stream to reactor	kg C (unconverted)/kg C(inflow to reactor)	$Y_{C,IN,unconverted/IN}$ = $1 - (Y_{C,X/IN} + Y_{C,Xi/IN} + Y_{C,CO2/IN})$

7.3.4 Nitrogen and phosphorus mass balances

The material balance for each reactor train is set up based on a mass balance on the element carbon. For each reactor, the yield based on carbon is determined for the conversion from the inflow organic components to biomass and products. The nitrogen and phosphorus material balances are estimated from the carbon balance, using factors of relative mass fractions normalised to carbon for each component.

The factors defining the relative mass fractions of the element of interest to carbon are given as follows: $F(J_k)_{i/C}$ where J_k refers to the component of interest, namely, biomass or product stream, and i refers to the element of interest, namely, nitrogen or phosphorous. For example, the relative mass fraction for nitrogen normalised to carbon for bacterial biomass, $F(X_{Bact})_{N/C}$ is given by the mass percentage nitrogen per mass percentage carbon. The relative weight fractions of nitrogen and phosphorus normalised to carbon for various stream components are shown in Appendix F.1.

7.3.5 Assumptions for mass balances in separation steps

In the integrated generic flowsheet for WWBRs (Figure 21), each separation is represented as a lumped operation (as a single step). In the detailed generic flowsheets for each reactor train (Figure 22, Figure 23, Figure 24 and Figure 25), the individual units involved are enumerated. Each separation step involves one or more separation unit with outflow streams of different compositions, and one or more splitter units with outflow streams having identical composition. In each bioreactor train, the outflow streams include a solids stream that is separated as a concentrated bottoms and/or product slurry.

Solids content of slurry

Solids content (SC) is defined as the mass of solids (dry mass) in slurry divided by the total mass of the slurry.

Solids Content Fraction (SC) = (mass of solids)/(mass of total slurry)

Liquid Content Fraction (LC) = (mass of liquid)/(mass of total slurry)

SC + LC = 1

Determination of the liquid content when the SC and the mass of solids are known:

	mass of total slurry	=	mass of solids/SC
Similarly,	mass of total slurry	=	mass of liquid/LC
thus,	mass of solids/SC	=	mass of liquid/LC
and,	LC	=	1 − SC
thus,	mass of solids/SC	=	mass of liquid/(1 − SC)
rearranging:	mass of liquid	=	((1 − SC)/SC) × mass of solids

The solids dry mass is calculated by dividing the total carbon in that stream by the carbon composition of the main component. For example, in separator 1.2:

$$N_{W(C2)} = (N_{C(C2)}/C_{comp,bact}) \times ((1 - SC_{C2})/SC_{C2})$$

Table 59: Overview of separation steps for removing solids in a generic WWBR

Unit number	Separation description	Relevant parameters	Solids content symbol
0	Primary Settling	Slurry solids content in "Solids to Bottoms" U1	$SC_{A1\text{-}4,U1}$
1	Bacterial Bioreactor Separation Train	Slurry solids content in "Solids (biomass) to Bottoms" U2	$SC_{C1,U2}$
2	Algal Bioreactor Separation Train	Slurry solids content in "Solids (biomass) to Bottoms" U3 and Product W3	$SC_{E1,U3}$ $SC_{E1,W3}$
3	Macrophyte Bioreactor Separation Train	Slurry solids content in "Solids to Bottoms" U4-5 and Products X1, X2 and X3	$SC_{G1,U4}$ $SC_{G1,X1}$ $SC_{G1,X2}$ $SC_{G1,X3}$
4	Solids Bioreactor Separation Train	Solids content in "Solids to Products" streams H2, H3 and Y4	SC_{H2} SC_{H3} SC_{Y4}

Factors used for separator units

In the detailed generic flowsheets, the type of separation that must take place is specified, but not the form of each separator. For each unit, it is assumed that product recovery will be optimised for the main product, so that residual biomass, secondary products and unconverted inflow goes to the bottoms with high recovery. The bottoms for each unit are assumed to behave as an entity, so that there is one recovery value for the entire secondary stream even though it may contain several separable constituents. The secondary stream may then undergo further separation.

eff_{STREAM} = separator unit efficiency with respect to the specified stream

Factors used for splitter units

Each splitter divides an entry stream into two exit streams of identical composition. One exit stream is regarded as primary, and the splitter ratio (r_{STREAM}) is assigned the subscript of that stream. In the model, this stream has been chosen to be the product-containing stream. Thus, the splitter streams that are bypass streams or are directed to the solids reactor are always the secondary streams. The ratio for both streams sums up to 1.

$$IN_{(\text{primary exit STREAM})} = IN_{(\text{entry STREAM})} \times r_{\text{primary exit STREAM}}$$

$$IN_{(\text{secondary exit STREAM})} = IN_{(\text{entry STREAM})} \times (1 - r_{\text{primary exit STREAM}})$$

7.4 Flowsheet and Mass Balance for the Bacterial Bioreactor Train

In the generalised WWBR flowsheet, the bacterial bioreactor is placed as the first treatment and production step in the WWBR. This was selected because the bacterial bioreactions are generally the most intensively operated, resulting in the greatest productivity per land area. It is also the best understood biological conversion system available, well developed to produce bioproducts with an established market. In addition, bacterial reactions usually demand a well-balanced nutrient supply and often produce VFAs as a by-product. These are retained in the improved compliance effluent and later removed by forming an important substrate supplement for the algal reactions.

The flowsheet for the primary handling of the feedstock followed by the bacterial reactor train is presented in Figure 22, with the accompanying unit descriptions and equations for the overall mass balance in Table 60 and the stream descriptions in Table 61. The symbols used for bacterial bioreactor yields (Table 62), and separator and splitter factors (Table 63) are presented. The equations for the mass balances for each unit are spelled out in the order in which they appear in the bacterial bioreactor train from Table 64 to Table 70.

Figure 22: Bacterial bioreactor train detailed flowsheet

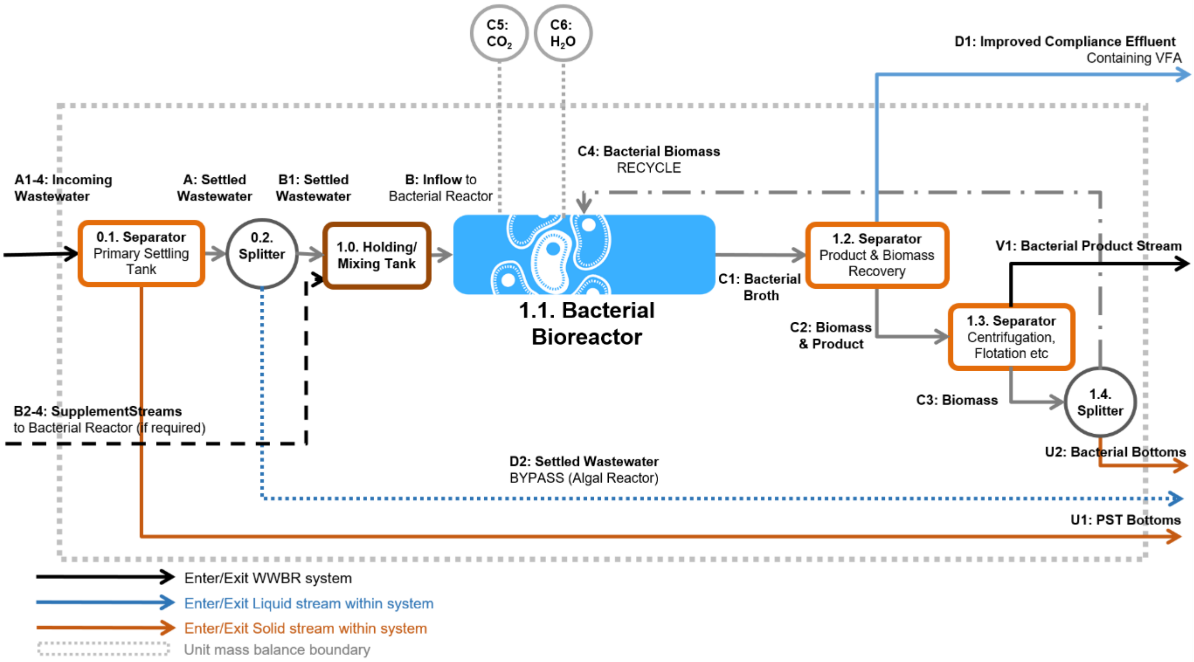


Table 60: Overall mass balance for bacterial bioreactor train

Unit number	Type	Unit description	Overall mass balance
0.1	Solid/Liquid Separator	PST settling raw wastewater, removing the bulk of the solids	(A1 + A2 + A3 + A4) − (A + U1) = 0
0.2	Splitter	Settled, raw wastewater to bacterial and algal reactors	(A) − (B1 + D2) = 0
1.0	Mixing Tank	Mixing supplementary substrate streams and providing buffer capacity to average flows and compositions	(B1 + B2 + B3 + B4) − (B) = 0
1.1	Reactor	Bacterial bioreactor	(B + C4 + C5 + C6) − (C1) = 0
1.2	Product and Biomass Recovery	Separates product and bacterial biomass from improved effluent (to algal reactor): this may occur within reactor	(C1) − (C2 + D1) = 0
1.3	DSP	DSP for separation of bacterial product from biomass or residual biomass: for example, centrifugation, flotation	(C2) − (C3 + V1) = 0
1.4	Splitter	Bacterial biomass to recycle and to Solids bioreactor	(C3) − (C4 + U2) = 0

It is noted that tank 1.0 may be used as a holding tank if required. Under these conditions, intermittent accumulation occurs and the material balance given will not apply on an instantaneous basis, but on a cyclical basis. Further, depending on product purity required and nature of product, DSP unit 1.3 may consist of multiple units.

Table 61: Streams in bacterial bioreactor train

Stream number	Stream description	Relation to process units	Relation to other streams Equations refer to mass balance (kg/day)
A1	Raw Wastewater A1	Into Unit 0.1: PST, Separator	Incoming stream, volume and composition chosen by user
A2	Raw Wastewater A2	Into Unit 0.1: PST, Separator	Incoming stream, volume and composition chosen by user (Optional stream)
A3	Raw Wastewater A3	Into Unit 0.1: PST, Separator	Incoming stream, volume and composition chosen by user (Optional stream)
A4	Raw Wastewater A4	Into Unit 0.1: PST, Separator	Incoming stream, volume and composition chosen by user (Optional stream)
A	Settled Raw Wastewater	Into Unit 0.2: Splitter	Mixed incoming stream, volume and composition a function of A1-A4, with solids removed A = (A1-4) − U1
B1	Settled Raw Wastewater	From Unit 0.2: Splitter Into Unit 1.0: Holding Tank	B1 = A − D2 Composition same as A, D2.
B2	Supplementary Feed	Into Unit 1.0: Holding Tank	Incoming stream, volume and composition set by user (Optional stream)
B3	Supplementary Feed	Into Unit 1.0: Holding Tank	Incoming stream, volume and composition set by user (Optional stream)
B4	Supplementary Feed	Into Unit 1.0: Holding Tank	Incoming stream, volume and composition set by user (Optional stream)
B	Mixed Inflow Stream	From Unit 1.0: Holding Tank Into Unit 1.1: Bacterial Bioreactor	B = B1 + B2 + B3 + B4 Composition composite
C1	Bacterial Broth	From Unit 1.1: Bacterial Bioreactor Into Unit 1.2: Separator	C1 = B + C4 + C5 + C6 Composition changed from B1
C2	Bacterial Biomass and Product	Main Solids Component from Unit 1.2 Into separator Unit 1.3	Solids composition similar to Solids in C1 Volume low, wet biomass
C3	Biomass	From Unit 1.3: Separator Into Unit 1.4: Splitter	Composition changed from C2, volume also less
C4	Bacterial Biomass Recycle	From Unit 1.4: Splitter Into Unit 1.1: Bacterial Bioreactor	C4 = C3 − U2 Composition same as C3
C5	CO_2	From Unit 1.1: Bacterial Bioreactor to Atmosphere	CO_2 only
C6	H_2O	Between Unit 1.1: Bacterial Bioreactor and Atmosphere	H_2O only
D1	Improved Compliance Effluent	From Unit 1.2: Separator Into Unit 2.1: Algal Bioreactor	D = C1 − C2 Composition same as dissolved composition C1
D2	Settled Raw Wastewater	From Unit 0.2: Splitter Into Unit 2.0: Holding Tank for Algal Bioreactor	D2 = A − B1 Composition same as A, B1
U2	Bacterial Biomass	From Unit 1.4: Splitter Into Unit 4.1: Solids Bioreactor	U2 = C3 − C4 Composition based on bacterial biomass
V1	Bacterial Product Stream	From Unit 1.3: Separator Exit system	V1 = B × Bacterial bioproduct yield coefficient × Separation efficiencies composition as specified by user

Table 62: Bacterial bioreactor yields

Conversion description	Unit	Symbol of factor
Mass of carbon reporting to bacterial biomass as a fraction of that present in influent stream to bacterial reactor (B)	kg C(Bacterial Biomass)/kg C(inflow Bacterial Bioreactor)	$Y_{C,XBact/IN}$
Mass of carbon reporting to product V1 as a fraction of that present in influent stream to bacterial reactor (B)	kg C(Product V1)/kg C(Inflow Bacterial Bioreactor)	$Y_{C,V1/IN}$
Mass of carbon reporting to interim product VFA as a fraction of that present in influent stream to bacterial reactor (B)	kg C(VFA)/kg C(Inflow Bacterial Bioreactor)	$Y_{C,VFA/IN}$
Mass of carbon leaving as CO_2 as a fraction of that present in influent stream to reactor (B)	kg C(CO_2 Bacterial Respiration)/kg C(Inflow Bacterial Bioreactor)	$Y_{C,CO2Bact/IN}$

Conversion description	Unit	Symbol of factor
Mass of carbon remaining unconverted as a fraction of that present in influent stream to reactor (B)	kg C (Unconverted)/kg C(Inflow Bacterial Bioreactor)	$Y_{C,INBact,unconverted/IN} = 1 - (Y_{C,XBact/IN} + Y_{C,V1/IN} + Y_{C,VFA/IN} + Y_{C,CO2Bact/IN})$

Table 63: Factors for separator and splitter units in bacterial bioreactor train

Unit number	Separator description	Relevant parameters	Factor symbol
0.1	Primary Settling	Slurry solids content Solids to Bottoms U1	SC_{U1} eff_{U1}
1.2	Product and Biomass Recovery	Slurry solids content Solids to Bottoms C2	SC_{C2} eff_{C2}
1.3	Bacterial Product Recovery	Slurry solids content Bacterial product recovery efficiency Solids (Biomass) to Bottoms C3	SC_{C3} eff_{V1} eff_{C3}
Unit number	**Splitter Description**	**Streams split**	**Split ratio symbol**
0.2	Raw Settled Wastewater	Fraction to Bacterial Bioreactor B1 Fraction to Algal Bioreactor D2	r_{B1} $1 - r_{B1}$
1.4	Bacterial Biomass Recycle	Fraction to Bacterial Bioreactor C4 Fraction to Solids Bioreactor U2	r_{C4} $1 - r_{C4}$

7.4.1 Mass balances for primary handling of feedstock

Before the bacterial bioreactor train *per se*, the wastewater feedstock streams must be mixed (if there are multiple streams) and separated to remove solids and potentially to allow a bypass. The PST (Unit 0.1; Table 64) receives the feedstock and the liquid component of settled wastewater (A) flows to the splitter (Unit 0.2; Table 65) where the main stream (B1) goes into the bacterial bioreactor train and a secondary stream (D2) is sent in a bypass directly to the algal bioreactor train (Section 7.4.1). This is an optional stream that may be needed if the effluent from the bacterial bioreactor stream contains insufficient total nutrients to operate the algal bioreactor. The solids slurry (U1) is taken as bottoms direct to the solids bioreactor train (Section 7.4.1).

Table 64: Mass balance for Unit 0.1 Separator: PST

Carbon Mass Balance: Unit 0.1: Separator: PST			
Carbon Fraction	**A1, A2, A3, A4: Incoming Wastewater**	**A: Settled Wastewater**	**U1: PST Bottoms to Solids Bioreactor**
Unconverted Carbon $IN_{C,liq}$ Liquid fraction	$IN_{C(A1\text{-}A4)liq} = Q_{(A1)liq} \times C_{C(A1)liq} + Q_{(A2)liq} \times C_{C(A2)liq} + Q_{(A3)liq} \times C_{C(A3)liq} + Q_{(A4)liq} \times C_{C(A4)liq}$	$IN_{C(A)liq} = IN_{C(A1\text{-}A4)liq} \times (N_{W(A)}/N_{W(A1\text{-}A4)})$	$IN_{C(U1)liq} = IN_{C(A1\text{-}A4)liq} \times (N_{W(U1)}/N_{W(A1\text{-}A4)})$
Unconverted Carbon $IN_{C,sol}$ Solid fraction	$IN_{C(A1\text{-}A4)sol} = Q_{(A1)sol} \times C_{C(A1)sol} + Q_{(A2)sol} \times C_{C(A2)sol} + Q_{(A3)sol} \times C_{C(A3)sol} + Q_{(A4)sol} \times C_{C(A4)sol}$	$IN_{C(A)sol} = IN_{C(A1\text{-}A4)sol} \times (1 - eff_{U1})$	$IN_{C(U1)sol} = IN_{C(A1\text{-}A4)sol} \times eff_{U1}$
Totals	$N_{C(A1\text{-}A4)} = IN_{C(A1\text{-}A4)liq} + IN_{C(A1\text{-}A4)sol}$	$N_{C(A)} = IN_{C(A)liq} + IN_{C(A)sol}$	$N_{C(U1)} = IN_{C(U1)liq} + IN_{C(U1)sol}$
Checks: Total stream amounts: $(N_{C(A1\text{-}A4)}) - (N_{C(A)} + N_{C(U1)}) = 0$ After the PST, it is assumed that any solids still in the stream are hydrolysed and incorporated into the dissolved component. The dissolved component in the solids fraction is assumed to be easily biodegradable and follows the biocatalysis in the solids reactor like the solids.			

Nitrogen Mass Balance: Unit 0.1: Separator: PST			
Nitrogen Fraction	**A1, A2, A3, A4: Incoming Wastewater**	**A: Settled Wastewater**	**U1: PST Bottoms to Solids Bioreactor**
Nitrogen Liquid Fraction	$IN_{N(A1\text{-}A4)liq} = Q_{(A1)liq} \times C_{N(A1)liq} + Q_{(A2)liq} \times C_{N(A2)liq} + Q_{(A3)liq} \times C_{N(A3)liq} + Q_{(A4)liq} \times C_{N(A4)liq}$	$IN_{N(A)liq} = IN_{N(A1\text{-}A4)liq} \times (N_{W(A)}/N_{W(A1\text{-}A4)})$	$IN_{N(U1)liq} = IN_{N(A1\text{-}A4)liq} \times (N_{W(U1)}/N_{W(A1\text{-}A4)})$
Unconverted Nitrogen Solid Fraction	$IN_{C(A1\text{-}A4)sol} = Q_{(A1)sol} \times C_{C(A1)sol} + Q_{(A2)sol} \times C_{C(A2)sol} + Q_{(A3)sol} \times C_{C(A3)sol} + Q_{(A4)sol} \times C_{C(A4)sol}$	$IN_{N(A)sol} = IN_{N(A1\text{-}A4)sol} \times (1 - eff_{U1})$	$IN_{N(U1)sol} = IN_{N(A1\text{-}A4)sol} \times eff_{U1}$
Totals	$N_{N(A1\text{-}A4)} = IN_{N(A1\text{-}A4)liq} + IN_{N(A1\text{-}A4)sol}$	$N_{N(A)} = IN_{N(A)liq} + IN_{N(A)sol}$	$N_{N(U1)} = IN_{N(U1)liq} + IN_{N(U1)sol}$

Checks: Total stream amounts:
$(N_{N(A1\text{-}A4)}) - (N_{N(A)} + N_{N(U1)}) = 0$
After the PST, it is assumed that any solids still in the stream are hydrolysed and incorporated into the dissolved component.
The dissolved component in the solids fraction is assumed to be easily biodegradable and follows the biocatalysis in the solids reactor like the solids.

Phosphorous Mass Balance: Unit 0.1: Separator: PST			
Phosphorous Fraction	**A1, A2, A3, A4: Incoming Wastewater**	**A: Settled Wastewater**	**U1: PST Bottoms to Solids Bioreactor**
Unconverted Phosphorous Liquid Fraction	$IN_{P(A1\text{-}A4)liq} = Q_{(A1)liq} \times C_{P(A1)liq} + Q_{(A2)liq} \times C_{P(A2)liq} + Q_{(A3)liq} \times C_{P(A3)liq} + Q_{(A4)liq} \times C_{P(A4)liq}$	$IN_{P(A)liq} = IN_{P(A1\text{-}A4)liq} \times (N_{W(A)}/N_{W(A1\text{-}A4)})$	$IN_{P(U1)liq} = IN_{P(A1\text{-}A4)liq} \times (N_{W(U1)}/N_{W(A1\text{-}A4)})$
Unconverted Phosphorous Solid Fraction	$IN_{P(A1\text{-}A4)sol} = Q_{(A1)sol} \times C_{P(A1)sol} + Q_{(A2)sol} \times C_{P(A2)sol} + Q_{(A3)sol} \times C_{P(A3)sol} + Q_{(A4)sol} \times C_{P(A4)sol}$	$IN_{P(A)sol} = IN_{P(A1\text{-}A4)sol} \times (1 - eff_{U1})$	$IN_{P(U1)sol} = IN_{P(A1\text{-}A4)sol} \times eff_{U1}$
Totals	$N_{P(A1\text{-}A4)} = IN_{P(A1\text{-}A4)liq} + IN_{P(A1\text{-}A4)sol}$	$N_{P(A)} = IN_{P(A)liq} + IN_{P(A)sol}$	$N_{P(U1)} = IN_{P(U1)liq} + IN_{P(U1)sol}$

Checks: Total stream amounts:
$(N_{P(A1\text{-}A4)}) - (N_{P(A)} + N_{P(U1)}) = 0$
After the PST, it is assumed that any solids still in the stream are hydrolysed and incorporated into the dissolved component.
The dissolved component in the solids fraction is assumed to be easily biodegradable and follows the biocatalysis in the solids reactor like the solids.

Water Mass Balance: Unit 0.1: Separator: PST			
Water Fraction	**A1, A2, A3, A4: Incoming Wastewater**	**A: Settled Wastewater**	**U1: PST Bottoms to Solids Bioreactor**
Total Water	$N_{W(A1\text{-}A4)} = N_{W(A1)liq} + N_{W(A2)liq} + N_{W(A3)liq} + N_{W(A4)liq}$	$N_{W(A)} = N_{W(A1\text{-}A4)} - N_{W(U1)}$	$N_{W(U1)} = N_{TOTAL(A1\text{-}4)sol} \times ((1 - SC_{U1})/SC_{U1})$

Checks: Total stream amounts:
$N_{W(A1\text{-}A4)} - N_{W(A)} - N_{W(U1)} = 0$
This only considers the water in the liquid fraction. While the solids component has hydrogen and oxygen (C + N + P < 1), this is associated with for example carbohydrates. While there may be interstitial water associated between solids particles, these are not considered for this mass balance.
The value of the total solids content of stream U1 is set by the solids content of the incoming streams. The water in the stream is determined by the solids content in the slurry after settling.

Table 65: Mass balance for Unit 0.2 Splitter: settled wastewater to bacterial bioreactor and bypass

Carbon, Nitrogen, Phosphorous and Water Mass Balance: Unit 0.2: Splitter			
Fraction	**A: Settled Wastewater**	**B1: Settled Wastewater**	**D2: Settled Wastewater Bypass (Algal Reactor)**
Total Carbon	$N_{C(A)}$	$N_{C(B1)} = N_{C(A)} \times r_{B1}$	$N_{C(D2)} = N_{C(A)} \times (1 - r_{B1})$
Total Nitrogen	$N_{N(A)}$	$N_{N(B1)} = N_{N(A)} \times r_{B1}$	$N_{N(D2)} = N_{N(A)} \times (1 - r_{B1})$
Total Phosphorous	$N_{P(A)}$	$N_{P(B1)} = N_{P(A)} \times r_{B1}$	$N_{P(D2)} = N_{P(A)} \times (1 - r_{B1})$
Total Water	$N_{W(A)}$	$N_{W(B1)} = N_{W(A)} \times r_{B1}$	$N_{W(D2)} = N_{W(A)} \times (1 - r_{B1})$
Checks: Total stream amounts: $(N_{C(A)}) - (N_{C(B1)} + N_{C(D2)}) = 0$ $(N_{N(A)}) - (N_{N(B1)} + N_{N(D2)})) = 0$ $(N_{P(A)}) - (N_{P(B1)} + N_{P(D2)}) = 0$ $(N_{W(A)}) - (N_{W(B1)} + N_{W(D2)}) = 0$			

7.4.2 Mass balances of mixing tank and bacterial bioreactor

The bacterial bioreactor train begins with a mixing tank (Unit 1.0; Table 66) that receives the settled wastewater from the primary handling (B1) as influent together with any supplementary nutrient streams (B2-4). This unit may perform a holding function if the bacterial bioreactor is operated in semi-batch mode or if the incoming wastewater feedstock streams have an inconstant flow rate; however, this mass balance ignores temporary accumulation in these situations with the assumption that this is adequate for early-stage feasibility assessment. The combined emerging stream (B) forms the inflow to the bacterial reactor (Unit 1.1; Table 67). Many bacterial reactors will need a mechanism for increasing the biomass residence time, and an optional biomass recycling stream (C4) is included. The bacterial respiration will release carbon dioxide to atmosphere (C5) and, depending on the reactor type and configuration, water may enter or leave the system (C6) through precipitation or evaporation.

Table 66: Mass balance for Unit 1.0 Mixing Tank: bacterial bioreactor inflow

Carbon, Nitrogen, Phosphorous and Water Mass Balance: Unit 1.0: Mixing Tank			
Fraction	**B1: Settled Wastewater**	**B2-4 Supplement Streams**	**B: Inflow to Bacterial Bioreactor**
Total Carbon	$N_{C(B1)} = N_{C(A)} \times r_{B1}$	$N_{C(B2\text{-}4)} = Q_{(B2)} \times C_{C(B2)} + Q_{(B3)} \times C_{C(B4)} + Q_{(B4)} \times C_{C(B4)}$	$N_{C(B)} = N_{C(B1)} + N_{C(B2\text{-}4)}$
Total Nitrogen	$N_{N(B1)} = N_{N(A)} \times r_{B1}$	$N_{N(B2\text{-}4)} = Q_{(B2)} \times C_{N(B2)} + Q_{(B3)} \times C_{N(B3)} + Q_{(B4)} \times C_{N(B4)}$	$N_{N(B)} = N_{N(B1)} + N_{N(B2\text{-}4)}$
Total Phosphorous	$N_{P(B1)} = N_{P(A)} \times r_{B1}$	$N_{P(B2\text{-}4)} = Q_{(B2)} \times C_{P(B2)} + Q_{(B3)} \times C_{P(B3)} + Q_{(B4)} \times C_{P(B4)}$	$N_{P(B)} = N_{P(B1)} + N_{P(B2\text{-}4)}$
Total Water	$N_{W(B1)} = N_{W(A)} \times r_{B1}$	$N_{W(B2\text{-}4)} = N_{W(B2)} + N_{W(B3)} + N_{W(B4)}$	$N_{W(B)} = N_{W(B1)} + N_{W(B2\text{-}4)}$
Checks: Total stream amounts: $(N_{C(B1)} + N_{C(B2\text{-}4)}) - (N_{C(B)}) = 0$ $(N_{N(B1)} + N_{N(B2\text{-}4)}) - (N_{N(B)}) = 0$ $(N_{P(B1)} + N_{P(B2\text{-}4)}) - (N_{P(B)}) = 0$ $(N_{W(B1)} + N_{W(B2\text{-}4)}) - (N_{W(B)}) = 0$ The substrate streams B2, B3 and B4 are assumed to have negligible solids component.			

Table 67: Mass balance for Unit 1.1 Bacterial Bioreactor

Carbon Mass Balance: Unit 1.1: Bacterial Bioreactor					
Carbon Fraction	**B: Inflow to Bacterial Bioreactor**	**C1: Bacterial Broth**	**C4: Bacterial Biomass Recycle**	**C5: CO_2 Release = Outflow**	**C6: H_2O**
Biomass $X_{Bacterial}$		$X_{C(C1)} = N_{C(B)} \times Y_{XBacterial/C} + X_{C(C4)}$	$X_{C(C4)} = X_{C(C3)} \times r_{C4}$		
Product P_{V1}		$P_{V1,C(C1)} = N_{C(B)} \times Y_{P,V1/C} + P_{V1,C(C4)}$	$P_{V1,C(C4)} = P_{V1,C(C3)} \times r_{C4}$		
Product P_{VFA}		$P_{VFA,C(C1)} = N_{C(B)} \times Y_{P,VFA/C} + P_{VFA,C(C4)}$	$P_{VFA,C(C4)} = P_{VFA,C(C3)} \times r_{C4}$		
Carbon Dioxide $CO_{2Bacterial}$				$CO_{2C,Bacterial(C5)} = N_{C(B)} \times Y_{CO2Bacterial/C}$	
Unconverted Carbon	$IN_{C(B)} = N_{C(B)} = N_{C(B1)} + N_{C(B2-4)}$	$IN_{C(C1)} = N_{C(B)} \times (1 - (Y_{XBacterial/C} + Y_{P,V1/C} + Y_{P,VFA/C} + Y_{CO2Bacterial/C}))$	$IN_{C(C4)} = IN_{C(C3)} \times r_{C4}$		
Totals	$N_{C(B)} = IN_{C(B)}$	$N_{C(C1)} = X_{C(C1)} + P_{V1,C(C1)} + P_{VFA,C(C1)} + IN_{C(C1)}$	$N_{C(C4)} = X_{C(C4)} + P_{V1,C(C4)} + P_{VFA,C(C4)} + IN_{C(C4)}$	$N_{C(C5)} = CO_{2Bacterial(C5)}$	
Checks: Total stream amounts: $(N_{C(B)} + N_{C(C4)} + N_{C(C5)}) - (N_{C(C1)}) = 0$					

Nitrogen Mass Balance: Unit 1.1: Bacterial Bioreactor					
Nitrogen Fraction	**B: Inflow to Bacterial Bioreactor**	**C1: Bacterial Broth**	**C4: Bacterial Biomass Recycle**	**C5: CO_2 Release = Outflow**	**C6: H_2O**
Biomass $X_{Bacterial}$		$X_{N(C1)} = X_{C(C1)} \times f(X_{bact})_{N/C}$	$X_{N(C4)} = X_{C(C4)} \times f(X_{bact})_{N/C}$		
Product P_{V1}		$P_{V1,N(C1)} = P_{V1,C(C1)} \times f(V1)_{N/C}$	$P_{V1,N(C4)} = P_{V1,C(C4)} \times f(V1)_{N/C}$		
Unconverted Nitrogen	$IN_{N(B)} = N_{N(B)} = N_{N(B1)} + N_{(B2-4)}$	$IN_{N(C1)} = IN_{N(B)} - X_{N(C1)} - P_{V1,N(C1)}$	$IN_{N(C4)} = IN_{N(C3)} \times r_{C4}$		
Totals	$N_{N(B)} = IN_{N(B)}$	$N_{N(C1)} = X_{N(C1)} + P_{V1,N(C1)} + IN_{N(C1)}$	$N_{N(C4)} = X_{N(C4)} + P_{V1,N(C4)} + IN_{N(C4)}$		
Checks: Total stream amounts: $(N_{N(B)} + N_{N(C4)}) - (N_{N(C1)}) = 0$					

Phosphorous Mass Balance: Unit 1.1: Bacterial Bioreactor					
Phosphorous Fraction	**B: Inflow To Bacterial Bioreactor**	**C1: Bacterial Broth**	**C4: Bacterial Biomass Recycle**	**C5: CO2 Release = outflow**	**C6: H_2O**
Biomass $X_{Bacterial}$		$X_{P(C1)} = X_{C(C1)} \times f_{(XBact)P/C}$	$X_{N(C4)} = X_{C(C4)} \times f_{(XBact)P/C}$		
Product P_{V1}		$P_{V1,P(C1)} = P_{V1,C(C1)} \times f_{(V1)P/C}$	$P_{V1,N(C4)} = P_{V1,C(C4)} \times f_{(V1)P/C}$		
Unconverted Phosphorous	$IN_{P(B)} = N_{P(B)} = N_{P(B1)} + N_{P(B2-4)}$	$IN_{P(C1)} = IN_{P(B)} - X_{P(C1)} - P_{V1,P(C1)}$	$IN_{P(C4)} = IN_{P(C3)} \times r_{C4}$		
Totals	$N_{P(B)} = IN_{P(B)}$	$N_{P(C1)} = X_{P(C1)} + P_{V1,P(C1)} + IN_{N(C1)}$	$N_{P(C4)} = X_{P(C4)} + P_{V1,P(C4)} + IN_{P(C4)}$		
Checks: Total stream amounts: $(N_{P(B)} + N_{P(C4)}) - (N_{P(C1)}) = 0$					

Water Mass Balance: Unit 1.1: Bacterial Bioreactor					
	B: Inflow to Bacterial Bio-reactor	C1: Bacterial Broth	C4: Bacterial Biomass Recycle	C5: CO_2 Release = Outflow	C6: H_2O
Total Water	$N_{W(B)}$	$N_{W(C1)} = N_{W(B)} + N_{W(C4)} + N_{W(C6)}$	$N_{W(C4)}$		$N_{W(C6)} = (N_{W(B)} + N_{W(C4)}) \times (F_{rain} - F_{evap})$
$(N_{W(B)} + N_{W(C4)} + N_{W(C6)}) - (N_{W(C1)}) = 0$					

7.4.3 Mass balance for first separation step for bacterial bioreactor outflow

The bacterial broth (C1) emerging from the reactor includes product, biomass and the changed composition liquid; this stream enters a series of separator and splitter units to recover the necessary streams. The first separator (Unit 1.2; Table 68) is operated to remove all biomass and product and sends the changed composition water stream (D1) to the algal reactor train as the main influent (Section 7.5.1). This stream has both improved compliance towards ultimate reuse, by removing nutrients, and increased suitability as an inflow feed for the algal reactor through the VFAs produced and nitrogen and phosphorous components liberated as interim products in the bacterial reactor and potential nutrients for the algal bioreactor.

Table 68: Mass balance for Unit 1.2 Separator: bacterial biomass and bacterial product V1 from improved compliance effluent

Carbon Mass Balance: Unit 1.2: Separator			
Carbon Fraction	C1: Bacterial Broth Outflow	C2: Biomass and Product	D1: Improved Compliance Effluent
Biomass $X_{Bacterial}$	$X_{C(C1)} = ((N_{C(B2)} + N_{C(B4-6)}) \times Y_{XBacterial/C}) + X_{C(C4)}$	$X_{C(C2)} = X_{C(C1)} \times eff_{C2}$	$X_{C(D1)} = X_{C(C1)} \times (1 - eff_{C2})$
Product P_{V1}	$P_{V1,C(C1)} = N_{C(B)} \times Y_{P,V1/C} + P_{V1,C(C4)}$	$P_{V1,C(C2)} = P_{V1,C(C1)} \times eff_{C2}$	$P_{V1,C(D1)} = P_{V1,C(C1)} \times (1 - eff_{C2})$
Product P_{VFA}	$P_{VFA,C(C1)} = N_{C(B)} \times Y_{P,VFA/C} + P_{VFA,C(C4)}$	$P_{VFA,C(C2)} = P_{VFA,C(C1)} \times (N_{W(C2)}/N_{W(C1)})$	$P_{VFA,C(D1)} = P_{VFA,C(C1)} \times (N_{W(D1)}/N_{W(C1)})$
Unconverted Carbon	$IN_{C(C1)} = N_{C(B)} \times (1 - (Y_{XBacterial/C} + Y_{P,V1/C} + Y_{P,VFA/C} + Y_{CO2Bacterial/C}))$	$IN_{C(C2)} = IN_{C(C1)} \times (N_{W(C2)}/N_{W(C1)})$	$IN_{C(D1)} = IN_{C(C1)} \times (N_{W(D1)}/N_{W(C1)})$
Totals	$N_{C(C1)} = X_{C(C1)} + P_{V1,C(C1)} + P_{VFA,C(C1)} + IN_{C(C1)}$	$N_{C(C2)} = X_{C(C2)} + P_{V1,C(C2)} + P_{VFA,C(C2)} + IN_{C(C2)}$	$N_{C(D1)} = X_{C(D1)} + P_{V1,C(D1)} + P_{VFA,C(D1)} + IN_{C(D1)}$
Checks: Total stream amounts: $(N_{C(C1)}) - (N_{C(D1)} + N_{C(C2)}) = 0$ The fraction dissolved components (e.g. unconverted carbon, VFA) depend on the water split, which depends on the solids content of the bottoms stream.			

Nitrogen Mass Balance: Unit 1.2: Separator			
Nitrogen Fraction	**C1: Bacterial Broth Outflow**	**C2: Biomass and Product**	**D1: Improved Compliance Effluent**
Biomass $X_{Bacterial}$	$X_{N(C1)} = X_{C(C1)} \times f(X_{Bact})_{N/C}$	$X_{N(C2)} = X_{N(C1)} \times eff_{C2}$	$X_{N(D1)} = X_{N(C1)} \times (1 - eff_{C2})$
Product P_{V1}	$P_{V1,N(C1)} = P_{V1,C(C1)} \times f(V1)_{N/C}$	$P_{V1,N(C2)} = P_{V1,N(C1)} \times eff_{C2}$	$P_{V1,N(D1)} = P_{V1,N(C1)} \times (1 - eff_{C2})$
Product P_{VFA}	$P_{VFA,N(C1)} = P_{VFA,C(C1)} \times f(VFA)_{N/C}$	$P_{VFA,N(C2)} = P_{VFA,N(C1)} \times (N_{W(C2)}/N_{W(C1)})$	$P_{VFA,N(D1)} = P_{VFA,N(C1)} \times (N_{W(D1)}/N_{W(C1)})$
Unconverted Nitrogen	$IN_{N(C1)} = (N_{N(B)}) - (X_{N(C1)} + P_{V1,N(C1)} + P_{VFA,N(C1)})$	$IN_{N(C2)} = IN_{N(C1)} \times (N_{W(C2)}/N_{W(C1)})$	$IN_{N(D1)} = IN_{N(C1)} \times (N_{W(D1)}/N_{W(C1)})$
Totals	$N_{N(C1)} = X_{N(C1)} + P_{V1,N(C1)} + P_{VFA,N(C1)} + IN_{N(C1)}$	$N_{N(C2)} = X_{N(C2)} + P_{V1,N(C2)} + P_{VFA,N(C2)} + IN_{N(C2)}$	$N_{N(D1)} = X_{N(D1)} + P_{V1,N(D1)} + P_{VFA,N(D1)} + IN_{N(D1)}$
Checks: Total stream amounts: $(NN(C1)) - (NN(D1) + NN(C2)) = 0$			

Phosphorous Mass Balance: Unit 1.2: Separator			
Phosphorous Fraction	**C1: Bacterial Broth Outflow**	**C2: Biomass and Product**	**D1: Improved Compliance Effluent**
Biomass $X_{Bacterial}$	$X_{P(C1)} = X_{C(C1)} \times f(X_{Bact})_{P/C}$	$X_{P(C2)} = X_{P(C1)} \times eff_{C2}$	$X_{P(D1)} = X_{P(C1)} \times (1 - eff_{C2})$
Product P_{V1}	$P_{V1,P(C1)} = P_{V1,C(C1)} \times f(V1)_{P/C}$	$P_{I,P(C2)} = P_{I,P(C1)} \times eff_{C2}$	$P_{I,P(D1)} = P_{I,P(C1)} \times (1 - eff_{C2})$
Product P_{VFA}	$P_{VFA,P(C1)} = P_{VFA,C(C1)} \times f(VFA)_{P/C}$	$P_{VFA,P(C2)} = P_{VFA,P(C1)} \times (N_{W(C2)}/N_{W(C1)})$	$P_{VFA,P(D1)} = P_{VFA,P(C1)} \times (N_{W(D1)}/N_{W(C1)})$
Unconverted Phosphorous	$IN_{P(C1)} = (N_{P(B)}) - (X_{P(C1)} + P_{V1,P(C1)} + P_{VFA,P(C1)})$	$IN_{P(C2)} = IN_{P(C1)} \times (N_{W(C2)}/N_{W(C1)})$	$IN_{P(D1)} = IN_{P(C1)} \times (N_{W(D1)}/N_{W(C1)})$
Totals	$N_{P(C1)} = X_{P(C1)} + P_{V1,P(C1)} + P_{VFA,P(C1)} + IN_{P(C1)}$	$N_{P(C2)} = X_{P(C2)} + P_{V1,P(C2)} + P_{VFA,P(C2)} + IN_{P(C2)}$	$N_{P(D1)} = X_{P(D1)} + P_{V1,P(D1)} + P_{VFA,P(D1)} + IN_{P(D1)}$
Checks: Total stream amounts: $(N_{P(C1)}) - (N_{P(D1)} + N_{P(C2)}) = 0$			

Water Mass Balance: Unit 1.2: Separator			
	C1: Bacterial Broth Outflow	**C2: Biomass and Product**	**D1: Improved Compliance Effluent**
Total Water	$N_{W(C1)} = N_{W(B2)} + N_{W(B4\text{-}6)} + N_{W(C4)} - N_{W(C5)}$	$N_{W(C2)} = (N_{C(C2)}/C_{comp,bact}) \times ((1 - SC_{C2})/SC_{C2})$	$N_{W(D1)} = N_{W(C1)} - N_{W(C2)}$
Checks: Total stream amounts: $(N_{W(C1)}) - (N_{W(D1)} + N_{W(C2)}) = 0$ The value of the total solids content of stream C2 is estimated by dividing the kg carbon in stream C2 ($N_{C(C2)}$) by the carbon composition of bacterial biomass. This is an overestimation but is simplified by using the compositions of the product stream and residual VFA and unconverted carbon substrate.			

7.4.4 Mass balances for subsequent separation steps for bacterial bioreactor outflow

The biomass and product stream (C2) flows to a second, and probably more complex, separator or set of separators (Unit 1.3; Table 69) that is operated to select for a very pure product stream (V1) and sends the biomass slurry (C3) to a splitter (Unit 1.4; Table 70). Here a biomass recycling stream (C4) is returned to the bacterial reactor, with the balance of the slurry sent as bottoms (U2) to combine with the primary feedstock slurry (U1) in the solids bioreactor train (Section 7.5.3).

Table 69: Mass balance for Unit 1.3 Separator: bacterial biomass from bacterial product V1

Carbon Mass Balance: Unit 1.3: Separator			
Carbon Fraction	**C2: Biomass and Product**	**C3: Biomass**	**V1: Bacterial Product Stream**
Biomass $X_{Bacterial}$	$X_{C(C2)} = X_{C(C1)} \times eff_{C2}$	$X_{C(C3)} = X_{C(C2)} \times eff_{C3}$	$X_{C(V1)} = X_{C(C2)} \times (1 - eff_{C3})$
Product P_{V1}	$P_{V1,C(C2)} = P_{V1,C(C1)} \times eff_{C2}$	$P_{V1,C(C3)} = P_{V1,C(C2)} \times (1 - eff_{V1})$	$P_{V1,C(I)} = P_{V1,C(C2)} \times eff_{V1}$
Product P_{VFA}	$P_{VFA,C(D1)} = P_{VFA,C(C1)} \times (N_{W(D1)}/N_{W(C1)})$	$P_{VFA,C(C3)} = P_{VFA,C(C2)} \times (N_{W(C3)}/N_{W(C2)})$	$P_{VFA,C(V1)} = P_{VFA,C(C2)} \times (N_{W(V1)}/N_{W(C2)})$
Unconverted Carbon	$IN_{C(C2)} = IN_{C(C1)} \times (N_{W(D1)}/N_{W(C1)})$	$IN_{C(C3)} = IN_{C(C2)} \times (N_{W(C3)}/N_{W(C2)})$	$IN_{C(V1)} = IN_{C(C2)} \times (N_{W(V1)}/N_{W(C2)})$
Totals	$N_{C(C2)} = X_{C(C2)} + P_{V1,C(C2)} + P_{VFA,C(C2)} + IN_{C(C2)}$	$N_{C(C3)} = X_{C(C3)} + P_{V1,C(C3)} + P_{VFA,C(C3)} + IN_{C(C3)}$	$N_{C(V1)} = X_{C(V1)} + P_{V1,C(V1)} + P_{VFA,C(V1)} + IN_{C(V1)}$

Checks: Total stream amounts:
$(N_{C(C2)}) - (N_{C(V1)} + N_{C(C3)}) = 0$
The emphasis here is on recovery of Product V1, and it is assumed that the processes involved here brings about a concentration change of Product V1 as well, so that the carbon (and the other nutrients) mass balance of Product V1 cannot simply be linked to the water split.
Product stream V1 is not pure Product V1, and there is some water still associated with the product stream. If this is processed further, this water stream, $N_{W(V1)}$ is lost to DSP.

Nitrogen Mass Balance: Unit 1.3: Separator			
Nitrogen Fraction	**C2: Biomass and Product**	**C3: Biomass**	**V1: Bacterial Product Stream**
Biomass $X_{Bacterial}$	$X_{N(C2)} = X_{N(C1)} \times eff_{C2}$	$X_{N(C3)} = X_{N(C2)} \times eff_{C3}$	$X_{N(V1)} = X_{N(C2)} \times (1 - eff_{C3})$
Product P_{V1}	$P_{V1,N(C2)} = P_{V1,N(C1)} \times eff_{C2}$	$P_{V1,N(C3)} = P_{V1,N(C2)} \times (1 - eff_{V1})$	$P_{V1,N(V1)} = P_{V1,N(C2)} \times eff_{V1}$
Product P_{VFA}	$P_{VFA,N(C2)} = P_{VFA,N(C1)} \times (N_{W(C2)}/N_{W(C1)})$	$P_{VFA,N(C3)} = P_{VFA,N(C2)} \times (N_{W(C3)}/N_{W(C2)})$	$P_{VFA,N(V1)} = P_{VFA,N(C2)} \times (N_{W(V1)}/N_{W(C2)})$
Unconverted Nitrogen	$IN_{N(C2)} = IN_{N(C1)} \times (N_{W(C2)}/N_{W(C1)})$	$IN_{N(C3)} = IN_{N(C2)} \times (N_{W(C3)}/N_{W(C2)})$	$IN_{N(V1)} = IN_{N(C2)} \times (N_{W(V1)}/N_{W(C2)})$
Totals	$N_{N(C2)} = X_{N(C2)} + P_{V1,N(C2)} + P_{VFA,N(C2)} + IN_{N(C2)}$	$N_{N(C3)} = X_{N(C3)} + P_{V1,N(C3)} + P_{VFA,N(C3)} + IN_{N(C3)}$	$N_{N(V1)} = X_{N(V1)} + P_{V1,N(V1)} + P_{VFA,N(V1)} + IN_{N(V1)}$

Checks: Total stream amounts:
$(N_{N(C2)}) - (N_{N(V1)} + N_{N(C3)}) = 0$

Phosphorous Mass Balance: Unit 1.3: Separator			
Phosphorous Fraction	**C2: Biomass and Product**	**C3: Biomass**	**V1: Bacterial Product Stream**
Biomass $X_{Bacterial}$	$X_{P(C2)} = X_{P(C1)} \times eff_{C2}$	$X_{P(C3)} = X_{P(C2)} \times eff_{C3}$	$X_{P(V1)} = X_{P(C2)} \times (1 - eff_{C3})$
Product P_{V1}	$P_{V1,P(C2)} = P_{V1,P(C1)} \times eff_{C2}$	$P_{V1,P(C3)} = P_{V1,P(C2)} \times (1 - eff_{V1})$	$P_{V1,P(V1)} = P_{V1,P(C2)} \times eff_{V1}$
Product P_{VFA}	$P_{VFA,P(C2)} = P_{VFA,P(C1)} \times (1 - eff_{D1})$	$P_{VFA,P(C3)} = P_{VFA,P(C2)} \times (N_{W(C3)}/N_{W(C2)})$	$P_{VFA,P(V1)} = P_{VFA,P(C2)} \times (N_{W(V1)}/N_{W(C2)})$
Unconverted Phosphorous	$IN_{P(C2)} = IN_{P(C1)} \times (1 - eff_{D1})$	$IN_{P(C3)} = IN_{P(C2)} \times (N_{W(C3)}/N_{W(C2)})$	$IN_{P(V1)} = IN_{P(C2)} \times (N_{W(V1)}/N_{W(C2)})$
Totals	$N_{P(C2)} = X_{P(C2)} + P_{V1,P(C2)} + P_{VFA,P(C2)} + IN_{P(C2)}$	$N_{P(C3)} = X_{P(C3)} + P_{V1,P(C3)} + P_{VFA,P(C3)} + IN_{P(C3)}$	$N_{P(V1)} = X_{P(V1)} + P_{V1,P(V1)} + P_{VFA,P(V1)} + IN_{P(V1)}$

Checks: Total stream amounts:
$(N_{P(C2)}) - (N_{P(V1)} + N_{P(C3)}) = 0$

Water Mass Balance: Unit 1.3: Separator			
	C2: Biomass and Product	**C3: Biomass**	**V1: Bacterial Product Stream**
Total Water	$N_{W(C2)} = (N_{C(C2)}/C_{comp, bact}) \times ((1 - SC_{C2})/SC_{C2})$	$N_{W(C3)} = (N_{C(C3)}/C_{comp, bact}) \times ((1 - SC_{C3})/SC_{C3})$	$N_{W(V1)} = N_{W(C2)} - N_{W(C3)}$

Checks: Total stream amounts:
$(N_{W(C2)}) - (N_{W(V1)} + N_{W(C3)}) = 0$
The value of the total solids content of stream C3 is estimated by dividing the kg carbon in stream C3 ($N_{C(C3)}$) by the carbon composition of bacterial biomass.

Table 70: Mass balance for Unit 1.4 Splitter: bacterial biomass to recycle and bottoms

Carbon, Nitrogen, Phosphorous and Water Mass Balance: Unit 1.4: Splitter			
Fraction	**C3: Biomass**	**C4: Bacterial Biomass Recycle**	**U2: Bacterial Bottoms**
Total Carbon	$N_{C(C3)}$	$N_{C(C4)} = N_{C(C3)} \times r_{C4}$	$N_{C(U2)} = N_{C(C3)} \times (1 - r_{C4})$
Total Nitrogen	$N_{N(C3)}$	$N_{N(C4)} = N_{N(C3)} \times r_{C4}$	$N_{N(U2)} = N_{N(C3)} \times (1 - r_{C4})$
Total Phosphorous	$N_{P(C3)}$	$N_{P(C4)} = N_{P(C3)} \times r_{C4}$	$N_{P(U2)} = N_{P(C3)} \times (1 - r_{C4})$
Total Water	$N_{W(C3)}$	$N_{W(C4)} = N_{W(C3)} \times r_{C4}$	$N_{W(U2)} = N_{W(C3)} \times (1 - r_{C4})$
Checks: Total stream amounts: $(N_{C(C3)}) - (N_{C(C4)} + N_{C(U2)}) = 0$ $(N_{N(C3)}) - (N_{N(C4)} + N_{N(U2)}) = 0$ $(N_{P(C3)}) - (N_{P(C4)} + N_{P(U2)}) = 0$ $(N_{W(C3)}) - (N_{W(C4)} + N_{W(U2)}) = 0$			

7.5 Flowsheets and Mass Balances for Other Bioreactor Units

Having presented the overview flowsheet for the generic WWBR (Figure 21), the detailed generic flowsheet and complete tables of mass balance equations were reported for the primary feedstock handling and bacterial bioreactor train (Figure 22, Section 7.3). The corresponding detailed flowsheets for the algal (Figure 23, Section 7.5.1), macrophyte (Figure 24, Section 7.5.2) and solids (Figure 25, Section 7.5.3) bioreactor trains are presented with overview mass balance equations. The detailed mass balance equations for the three reactor trains in the generic WWBR can be found in Appendix F.

7.5.1 Flowsheet and mass balance for the algal bioreactor

In the generalised WWBR flowsheet presented as an example in this study, the algal bioreactor follows the bacterial bioreactor. The purpose in terms of the wastewater remediation aspect of the biorefinery is that the algal processes are expected to remove a high proportion of the nitrogen and phosphorus entering in the feedstock streams. In addition, the placement after the bacterial bioreactor allows for VFAs produced in the bacterial processes to become part of the inflow substrate for the algal bioreactor, thus enhancing its performance.

Figure 23 displays the algal bioreactor train with descriptions of units and related overall mass balance equations presented in Table 71. The streams enumerated in Table 72. The symbols used for algal bioreactor yields (Table 73), and separator and splitter factors (Table 74) are then given. Detailed equations for mass balances are presented in Appendix F.2.

The algal bioreactor train begins with a mixing tank (2.0) that receives the inflow streams. The inflow comprises primarily the improved compliance effluent (D1) from the bacterial bioreactor separator (1.2), which also contains VFAs produced in the bacterial process. Secondary inflow includes a possible stream of settled wastewater (D2) directly from the primary handling splitter (0.2) that bypasses the bacterial reactor. This option would be used only in the case where the main inflow from the bacterial bioreactor is too carbon-poor to serve the algal` bioreactor adequately. Additional minor inflow streams (D3-5) allow for supplementary nutrients. The mixed stream (D) exiting the mixing tank forms the inflow to the algal bioreactor (2.1). Most algal reactions include photosynthesis, with a nett absorption of carbon dioxide from atmosphere (E5) to supplement carbon available in the inflow stream. Most algal bioreactor designs will have a nett inflow or outflow of water (E6) through precipitation and evaporation.

The algal broth (E1) consists of the two algal products, namely, biomass and changed composition liquid. It flows out into the first separation unit (2.2) following the algal bioreactor where the now almost-compliant effluent (F1) is extracted, becoming the inflow for the macrophyte reactor train (Section 7.5.2). The bottoms from this separator are the biomass and product stream (E2), which are subjected to a more complex separation, which possibly includes cell breakage or other extraction methods. The algal products stream (E3) exiting this separator (2.3) undergoes a further (biphasic) separation (2.4), resulting in the algal bioproduct stream (W1), which is probably low-volume high-value, and the algal oil product stream (W2), both leaving the biorefinery system. Finally, the biomass stream (E4) may be split into a stream leaving the system (W3) as a biomass product and/or an algal bottoms stream (U2), which is sent to the solids bioreactor train (Section 7.5.3).

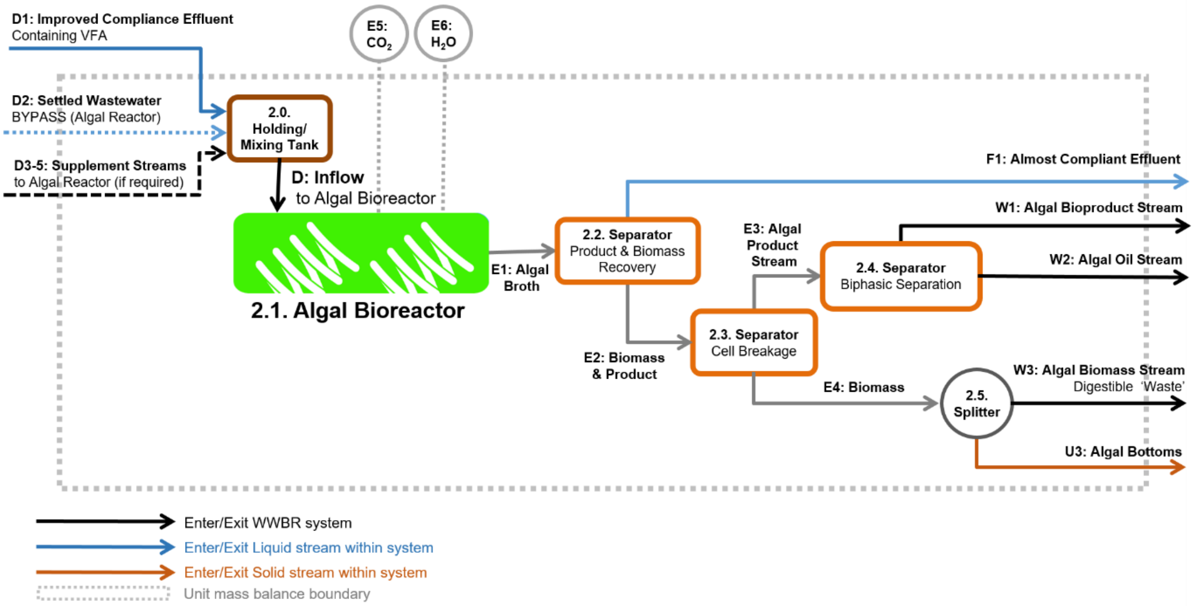


Figure 23: Algal bioreactor train detailed flowsheet

Table 71: Overall mass balance for algal bioreactor train

Unit number	Type	Unit description	Overall mass balance (In) − (Out) = 0
2.0	Holding Tank	Mixing supplementary substrate streams and providing buffer capacity to average flows and compositions	(D1 + D2 + D3 + D4 + D5) − (D) = 0
2.1	Algal Bioreactor	Algal bioreactor	(D + E5 + E6) − (E1) = 0
2.2	Product and Biomass Recovery	Separates product + algal biomass from improved effluent (to macrophyte bioreactor)	(E1) − (E2 + F1) = 0
2.3	Separator	DSP: cell breakage	(E2) − (E3 + E4) = 0
2.4	Separator	DSP: separates lipids and water-based products	(E3) − (W1 + W2) = 0
2.5	Splitter	Algal biomass to product stream (digestible algal biomass) and solids bioreactor	(E4) − (W3 + U3) = 0

Table 72: Streams in algal bioreactor train

Stream number	Stream description	Relation to process units	Relation to other streams Equations refer to mass balance (kg/day)
D1	Improved Compliance Effluent	From Unit 1.2: Separator Into Unit 2.0: Holding Tank for Algal Bioreactor	D1 = C1 − C2 Composition same as dissolved composition C1
D2	Settled Raw Wastewater	From Unit 0.2: Splitter Into Unit 2.0: Holding Tank for Algal Bioreactor	D2 = A − B1 Composition same as A and B1
D3	Supplementary Feed	Into Unit 2.0: Holding Tank for Algal Bioreactor	Incoming stream, volume and composition set by user (Optional stream)
D4	Supplementary Feed	Into Unit 2.0: Holding Tank for Algal Bioreactor	Incoming stream, volume and composition set by user (Optional stream)
D5	Supplementary Feed	Into Unit 2.0: Holding Tank for Algal Bioreactor	Incoming stream, volume and composition set by user (Optional stream)
D	Mixed Inflow Stream	From Unit 2.0: Holding Tank for Algal Bioreactor Into Unit 2.1: Algal Bioreactor	D = D1 + D2 + D3 + D4 + D5
E1	Algal Broth	From Unit 2.1: Algal Bioreactor Into Unit 2.2: Separator	E1 = D + E5 + E6 Composition changed from D

Stream number	Stream description	Relation to process units	Relation to other streams Equations refer to mass balance (kg/day)
E2	Biomass and Product	From Unit 2.2: Product and Biomass Recovery Into Unit 2.3: DSP	E2 = E1 − F1 Composition similar to solids component of E1
E3	Algal Product Stream	From Unit 2.3: Product and Biomass Recovery Into Unit 2.4: DSP	E3 = E2 − E4 Composition changed from E2
E4	Biomass	From Unit 2.3: Product and Biomass Recovery Into Unit 2.5: Splitter	E4 = E2 − E3 Composition changed from E2
E5	CO_2	From atmosphere Into Unit 2.1: Algal Bioreactor	CO_2 only
E6	H_2O	Between Unit 2.1: Algal Bioreactor and Atmosphere	H_2O only
F1	Almost-Compliant Effluent	From Unit 2.2: Separator Into Unit 3.0: Holding Tank for Macrophyte Bioreactor	F1 = E1 − E2 Composition same as dissolved composition E1
U3	Algal Biomass Not to Product Streams	From Unit 2.5: Splitter Into Unit 4.0: Holding Tank for Solids Bioreactor	Total algal biomass = U3 + W3 U3 = E1 − (F1 + W1 + W2 + W3) Composition same as W3
W1	Algal Bioproduct Stream	From Unit 2.4: Separator Exit system	W1 = D × Algal bioproduct yield coefficient × Separation efficiencies Composition as specified by user
W2	Algal Oil Stream	From Unit 2.4: Separator Exit system	W2 = D × Algal oil yield coefficient × Separation efficiencies Composition as specified by user
W3	Algal Biomass (digestible waste)	From Unit 2.5: Splitter Exit system	W3 = D − (F1 + W1 + W2 + U3) Note: U3 can be 0 Composition same as U3

Table 73: Algal bioreactor yields

Conversion description	Unit	Symbol of factor
Mass of carbon reporting to algal biomass as a fraction of that present in influent stream to reactor (D)	kg C(Algal Biomass)/kg C(Inflow Algal Bioreactor)	$Y_{C,XAlgal/IN}$
Mass of carbon reporting to algal product W1 as a fraction of that present in influent stream to reactor (D)	kg C(Product W1)/kg C(Inflow Algal Bioreactor)	$Y_{C,W1/IN}$
Mass of carbon reporting to algal product W2 as a fraction of that present in influent stream to reactor (D)	kg C(Product W2)/kg C(Inflow Algal Bioreactor)	$Y_{C,W2/IN} + Y_{CO2Algal/IN}$
Mass of carbon entering or leaving as CO_2 as a fraction of that present in influent stream to reactor (D)	kg C(CO_2 Algal Uptake)/kg C(Inflow Algal Bioreactor)	$Y_{C,CO2Algal/IN}$
Mass of carbon remaining unconverted as a fraction of that present in influent stream to reactor (D)	kg C (Unconverted)/kg C(Inflow Algal Bioreactor)	$Y_{C,INAlgal,unconverted/IN} = 1 - (Y_{C,XAlgal/IN} + Y_{C,W1/IN} + Y_{C,W2/IN})$

Table 74: Factors for separator and splitter units in algal bioreactor train

Unit number	Separator description	Relevant parameters	Efficiency symbol
2.2	Product and Biomass Recovery	Slurry Solids Content Solid to Bottoms E2	SC_{E2} eff_{E2}
2.3	Algal Product Recovery	Algal Bioproduct Recovery Efficiency Solids (biomass) to Bottoms E4 Solids to Bottoms E4	eff_{E3} eff_{E4} SC_{E4}
2.4	Algal Product Separation	Algal High-value Bioproduct Recovery Efficiency Algal Oil Recovery Efficiency Solids Content in Oil Recovery Solids Content in Algal Bioproduct	eff_{W1} eff_{W2} SC_{W2} SC_{W1}
Unit number	**Splitter description**	**Streams split**	**Ratio symbol**
2.5	Algal Biomass	Fraction to Algal Product W3 Stream Fraction to Solids Bioreactor U3	r_{W3} $1 - r_{W3}$

7.5.2 *Flowsheet and mass balance for the macrophyte bioreactor*

The generalised WWBR flowsheet places the macrophyte bioreactor immediately before release of the (now compliant) water stream into the environment, or to reuse. The macrophyte bioreactor functions as a long residence time, slow-acting reactor with multiple simultaneous mechanisms removing the last of the nutrients from the wastewater.

The macrophyte bioreactor train is diagrammed in Figure 24. The units with the corresponding overall mass balance equations (Table 75) and stream descriptions (Table 76) follow. Macrophyte bioreactor yield symbols are presented in Table 77, with the symbols for separator and splitter factors given in Table 78. The detailed mass balance equations for the macrophyte bioreactor train can be found in Appendix F.3.

The macrophyte bioreactor train may begin with a mixing tank (3.0) should supplementary nutrient streams (F2-4) be deemed necessary. The main influent component is the almost-compliant effluent stream (F1) from the algal bioreactor train (Section 7.5.1); once combined with possible supplementary nutrients, this forms the inflow (F) to the macrophyte bioreactor (3.1). Macrophytes always have a nett inflow of carbon dioxide from atmosphere (G4) through photosynthesis, which is considerably greater than respiration, and macrophyte bioreactors are usually exposed to the elements. Depending on the local climate, they have a nett inflow or outflow of water (G7) from precipitation and evaporation.

The wet biomass (G1) harvested from the macrophyte bioreactor, usually on a batch basis, goes through several separation processes. The first separator (3.2) removes the compliant effluent (Z) – the key product of the biorefinery that is either discharged into the environment or reused. The solids element from this separation is sent to a following separator (3.3) producing a fibre and biomass stream (G3) and a nitrogen- and phosphorus-rich sediment stream (G4). The fibre and biomass are separated in a further separation unit (3.4), with a fibre product stream (X1) and a cellulosic biomass stream emerging. The cellulosic biomass may be split into a product stream (X2), which exits the system, and/or a cellulosic biomass bottoms stream (U4), which is sent to the solids bioreactor train (Section 7.5.3). Likewise, the sediment may be split into a product stream (X3) and/or a sediment bottoms stream (U5) combining with the solids bioreactor train (Section 7.5.3) inflow.

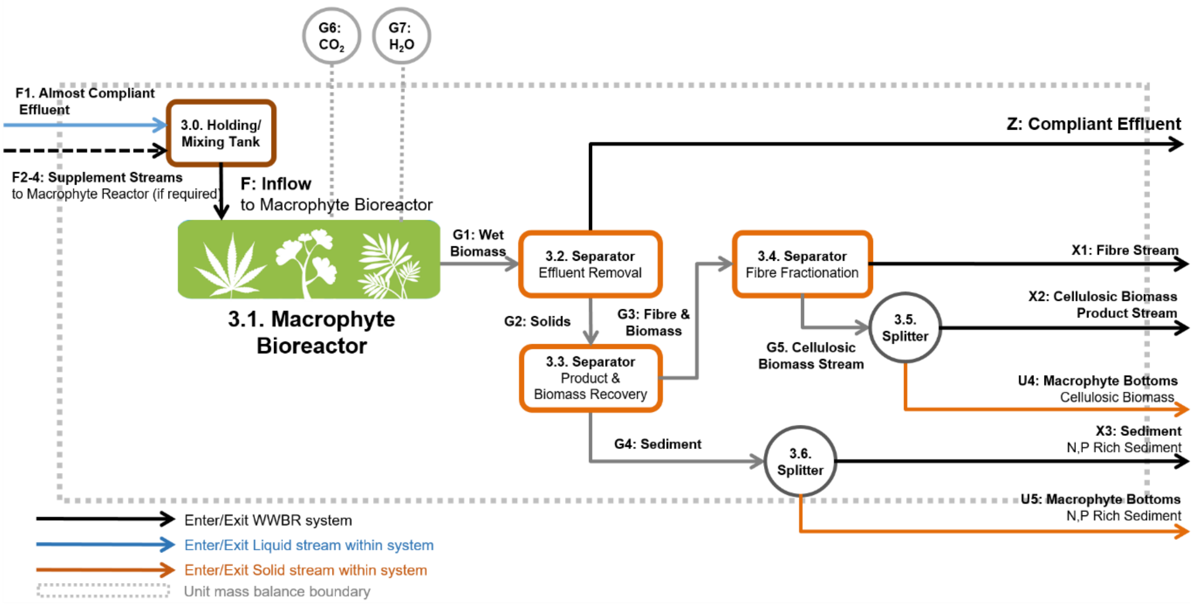


Figure 24: Macrophyte bioreactor train detailed flowsheet

Table 75: Overall mass balance for macrophyte bioreactor train

Unit number	Type	Unit description	Overall mass balance (In) − (Out) = 0
3.0	Holding/Mixing Tank	Mixing supplementary substrate streams and providing buffer capacity to average flows and compositions	(F1 + F2 + F3 + F4) − (F) = 0
3.1	Macrophyte Bioreactor	Macrophyte bioreactor	(F + G6 + G7) − (G1) = 0
3.2	Solid/Liquid Separator	Separates macrophyte biomass from compliant effluent (leaving system)	(G1) − (G2 + Z) = 0
3.3	Solid/Solid Separator	Separates biomass from sediment. This may involve separate steps, e.g. manual harvesting (seasonal), and sediment desludging (annual)	(G2) − (G3 + G4) = 0
3.4	Size Fractioning Separator	Macrophyte biomass harvested and fractionated into high-quality fibre and lower quality cellulosic biomass	(G3) − (G5 + X1) = 0
3.5	Splitter	Lower quality cellulosic biomass to solids bioreactor and to product stream (further processing)	(G5) − (X2 + U4) = 0
3.6	Splitter	Nitrogen- and phosphorous-rich sediment to product stream and to solids bioreactor	(G4) − (X3 + U5) = 0

Table 76: Streams in macrophyte bioreactor train

Stream number	Stream description	Relation to process units	Relation to other streams Equations refer to mass balance (kg/day)
F1	Almost-compliant Effluent	From Unit 2.2: Separator Into Unit 3.0: Holding Tank for Macrophyte Bioreactor	F = E1 − E2 Composition same as dissolved composition E1
F2	Supplementary Feed	Into Unit 3.0: Holding Tank for Macrophyte Bioreactor	Incoming stream, volume and composition set by user (Optional stream)
F3	Supplementary Feed	Into Unit 3.0: Holding Tank for Macrophyte Bioreactor	Incoming stream, volume and composition set by user (Optional stream)
F4	Supplementary Feed	Into Unit 3.0: Holding Tank for Macrophyte Bioreactor	Incoming stream, volume and composition set by user (Optional stream)
G1	Wet Macrophyte Biomass	From Unit 3.1: Macrophyte Bioreactor Into Unit 3.2: Separator	G1 = (F + G6 + G7) × (Macrophyte yield coefficient) × (Separation efficiencies) Composition changed from F1, a combination of liquid, fibre and sediment
G2	Solids	From Unit 3.2: Separator (Effluent Removal) Into Unit 3.3: Separator (Product and Biomass Recovery)	G2 = G1 − Z Macrophyte biomass as well as any sediment
G3	Fibre and Biomass	From Unit 3.3: Separator (Product and Biomass Recovery) Into Unit 3.4: Separator	G3 = G2 − G4
G4	Sediment	From Unit 3.3: Separator (Product and Biomass Recovery) Into Unit 3.6: Splitter	Slow accumulating sediment consisting of algal (dead) biomass, rich in nitrogen and phosphorous.
G5	Cellulosic Biomass Stream	From Unit 3.4: Separator Into Unit 3.5: Splitter	Similar composition to G3 Volume G5 = G3 − X1
G6	CO_2	From Atmosphere Into Unit 3.1: Macrophyte Bioreactor	CO_2 only
G7	H_2O	Between atmosphere and Unit 3.1: Macrophyte Bioreactor	H_2O only
U4	Macrophyte Bottoms (Cellulosic Biomass)	From Unit 3.5: Splitter Into Unit 4.0: Holding Tank for Solids Bioreactor	U4 = G5 − X2 Composition same as G5, X2
U5	Macrophyte Bottoms (Nitrogen-, Phosphorous-rich Sediment)	From Unit 3.6: Splitter Into Unit 4.0: Holding Tank for Solids Bioreactor	U5 = G4 − X3 Composition same as G4, X3
X1	Fibre Stream	From Unit 3.4: Separator Exit system	G × (1 − moisture content fraction) × (Fibre compositional fraction) × (Separation efficiencies)
X2	Cellulosic Biomass Product Stream	From Unit 3.5: Splitter Exit system	X2 = G5 − U4
X3	Nitrogen-, Phosphorous-rich Sediment	From Unit 3.6: Splitter Exit System	X3 = G4 − U5

Stream number	Stream description	Relation to process units	Relation to other streams Equations refer to mass balance (kg/day)
Z	Compliant Effluent	From Unit 3.2: Separator Exit System	Composition must comply with discharge standards (either for discharge into natural water body or for irrigation)

Table 77: Macrophyte bioreactor yields

Conversion description	Unit	Symbol of factor
Mass of carbon reporting to macrophyte biomass as a fraction of that present in influent stream to reactor (F)	kg C(Macrophyte Biomass)/kg C(Inflow Macrophyte Reactor)	$Y_{C,X,Macr/IN} = CO_{2C,Macrophyte(G6)}$
Mass of carbon entering as CO_2 as a fraction of that present in influent stream to reactor (F)	kg C(CO_2 Macrophyte Uptake)/kg C(Inflow Macrophyte Bioreactor)	$(Y_{C,macrophyte} \times C_{macrophyte} \times N_{W(F)})/365$
Mass of carbon reporting to bacterial biomass, as a sediment component, as a fraction of that present in influent stream to reactor (F)	kg C(Bacterial Biomass)/kg C(Inflow Macrophyte Reactor)	$Y_{C,X,Bact/IN}$
Mass of carbon remaining unconverted as a fraction of that present in influent stream to reactor (F)	kg C (Unconverted)/kg C(Inflow Macrophyte Bioreactor)	$1 - Y_{C,X,Bact/IN}$

Table 78: Factors for separator and splitter units in macrophyte bioreactor train

Unit number	Separator description	Relevant parameters	Efficiency symbol
3.2	Effluent removal	Solids to Bottoms G2 Slurry solids contents	eff_{G2} SC_{G2}
3.3	Product and biomass recovery	Biomass-to-biomass stream efficiency Sediment-to-sediment stream efficiency	eff_{G3} eff_{G4}
3.4	Fibre fractionation	Macrophyte fibre recovery Cellulosic biomass stream	eff_{X1} eff_{G5}
Unit number	**Splitter description**	**Streams split**	**Ratio symbol**
3.5	Macrophyte bottoms Cellulosic biomass	Fraction to cellulosic Product X2 stream Fraction to Solids Bioreactor U4	r_{X2} $1 - r_{X2}$
3.6	Macrophyte bottoms Nitrogen- and phosphorous-rich sediment	Fraction to Sediment Product X3 stream Fraction to Solids Bioreactor U5	r_{X3} $1 - r_{X3}$

7.5.3 Flowsheet and mass balance for the solids bioreactor

The solids bioreactor train is placed in the generalised WWBR to valorize and remediate the solids slurries from various parts of the WWBR. The detailed flowsheet for the solids bioreactor train is given in Figure 25, with a list of units and overall mass balance equations (Table 79) and a list of stream descriptions (Table 80) following. For the detailed mass balance equations see Appendix F.4.

The bottoms stream from the primary separation (0.1) of the combined influent wastewater streams (A1-4, Section 7.4) entering the WWBR, and the bottoms streams from each of the reactor trains are indicated. The solids bioreactor train begins with a mixing tank (4.0) in which the primary separation bottoms (U1, Section 7.4.1), bacterial biomass (U2, Section 7.4.4), algal biomass (U3, Section 7.5.1), macrophyte biomass (U4, Section 7.5.2) and macrophyte bioreactor sediment (U5, Section 7.5.2) are combined with supplementary nutrient streams (U4-6), which may be added if necessary, giving the inflow (U) to the solids bioreactor. As with other bioreactors, the solids bioreactor is expected to be a heterotrophic process, potentially fungal, hence has an outflow of carbon dioxide (H4) to atmosphere from respiration. Similarly, depending on the configuration of the bioreactor, it may have in- or outflow of water (H5) from precipitation and evaporation.

The solids bioreactor (4.1) produces a solids matrix (H1) that is most likely harvested periodically. This matrix goes to the first separator (4.1) in the solids train that recovers the crust/surface-related product (Y1) and sends the subsurface matrix (H2) to the second separator (4.3). Here a liquor-related product stream (Y2) is retrieved, with the pressed cake (H3) going to the final separator (4.4) yielding cake-related product (Y3) and compost (Y4). All these product streams exit the WWBR.

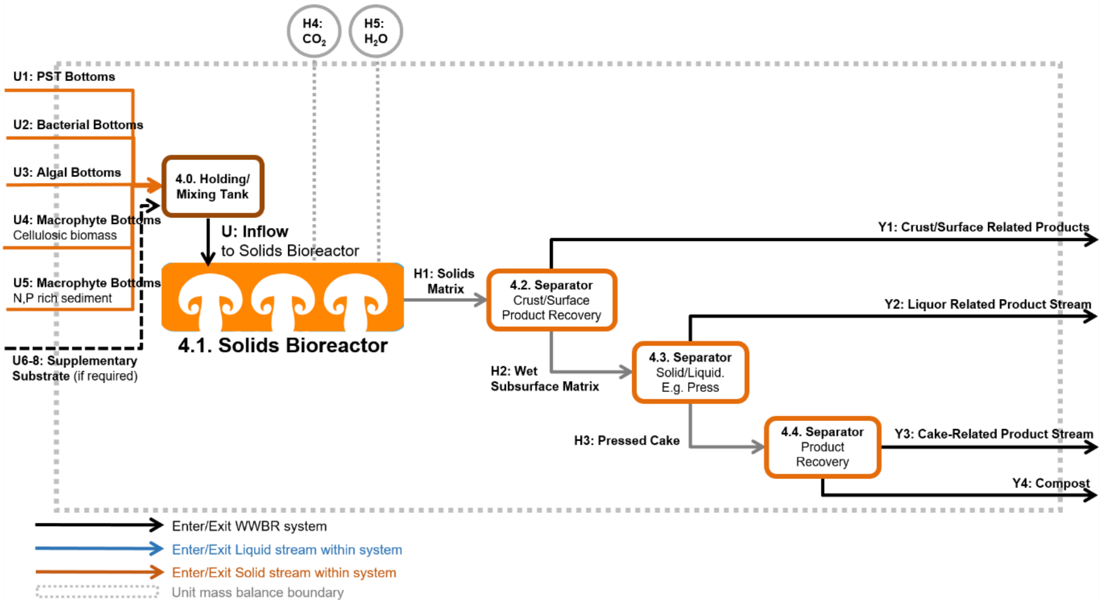


Figure 25: Solids bioreactor train detailed flowsheet

Table 79: Overall mass balance for solids bioreactor train

Unit Number	Type	Unit Description	Overall Mass Balance (In) – (Out) = 0
4.0	Holding Tank for Solids Bioreactor	Mixing supplementary feed and providing buffer capacity to average flows and compositions	(U1 + U2 + U3 + U4 + U5 + U6 + U7 + U8) − (U) = 0
4.1	Solids Bioreactor	Solids bioreactor	(U + H4 + H5) − (H1) = 0
4.2	Separator	Separates crust-associated (surface) products from rest of growth matrix	(H1) − (H2 + Y1) = 0
4.3	Separator	Solid/liquid separation, e.g. press to separate liquid medium from support matrix	(H2) − (H3 + Y2) = 0
4.4	Separator	Cake-related product recovery from residual compost	((H3) − (Y3 + Y4) = 0

Table 80: Streams in solids bioreactor train

Stream number	Stream description	Relation to process units	Relation to other streams Equations refer to mass balance (kg/day)
H1	Solids Matrix	From Unit 4.1 Solids Bioreactor Into Unit 4.2: Separator	H1 = U + H4 + H5 Composition complex
H2	Wet Subsurface Matrix	From Unit 4.2: Separator Into Unit 4.3: Separator	Composition different from H1, H3
H3	Pressed Cake	From Unit 4.3: Separator Into Unit 4.4: Separator	H3 = H2 − Y2 Low volume, less wet Composition: Similar to solids fraction of H2
H4	CO_2	From Unit 4.1: Solids Bioreactor to Atmosphere	CO_2 only
H5	H_2O	Between Atmosphere and Unit 4.1: Solids Bioreactor	H_2O only
U1	Biosolids (Main Fraction)	From Unit 0.1: Separator Into Unit 4.0: Holding Tank for Solids Bioreactor	Volume and composition set by user Dependent on PST efficiency set by user
U2	Bacterial Biomass	From Unit 1.4: Splitter Into Unit 4.0: Holding Tank for Solids Bioreactor	U2 = C1 − (D + V1 + C4) Composition based on bacterial biomass as set by user
U3	Algal Biomass not to Product Streams	From Unit 2.5: Splitter Into Unit 4.0: Holding Tank for Solids Bioreactor	Total algal biomass = U3 + W3 U3 = E1 − (F1 + W1 + W2 + W3) Composition same as L
U4	Macrophyte Bottoms: Cellulosic Biomass	From Unit 3.5: Splitter Into Unit 4.0: Holding Tank for Solids Bioreactor	U4 = G5 − X2 Composition same as X2

Stream number	Stream description	Relation to process units	Relation to other streams Equations refer to mass balance (kg/day)
U5	Macrophyte Bottoms: Nitrogen- and Phosphorous-rich Sediment	From Unit 3.6: Splitter Into Unit 4.0: Holding Tank for Solids Bioreactor	U5 = G4 − X3 Composition same as X3
U6	Supplementary Feed	Into Unit 4.0: Holding Tank for Solids Bioreactor	Incoming stream, volume and composition set by user (Optional stream)
U7	Supplementary Feed	Into Unit 4.0: Holding Tank for Solids Bioreactor	Incoming stream, volume and composition set by user (Optional stream)
U8	Supplementary Feed	Into Unit 4.0: Holding Tank for Solids Bioreactor	Incoming stream, volume and composition set by user (Optional stream)
Y1	Crust/Surface-related Product Stream	From Unit 4.2: Separator Exit system	H1 × Crust-related product yield × Separation efficiencies
Y2	Liquor-related Product Stream	From Unit 4.3: Separator Exit system	Y2 = H1 − H2 Y2 = H1 × (e.g.) Organic acid yield coefficient × Separation efficiencies Composition: Similar to dissolved fraction of H2
Y3	Cake-related Product Stream	From Unit 4.4: Separator Exit stream	Y3 = H1 × Cake-related product yield × Separation efficiencies
Y4	Compost	From Unit 4.4: Separator Exit stream	Y4 = H3 − Y3

Table 81: Solids bioreactor yields

Conversion description	Unit	Symbol of factor
Mass of carbon reporting to biomass as a fraction of that present in influent stream to reactor (U)	kg C(Biomass)/kg C(Inflow Solids Bioreactor)	$Y_{C,XSolids/IN} = Y_{C,Y1/IN} + Y_{C,Y3/IN}$
Mass of carbon reporting to Product Y1 (organic content in surface crust) as a fraction of that present in influent stream to reactor (U)	kg C(Product Y1)/kg C(Inflow Solids Bioreactor)	$Y_{C,Y1/IN}$
Mass of carbon reporting to Product Y2 (liquor-related product stream) as a fraction of that present in influent stream to reactor (U)	kg C(Product Y2)/kg C(Inflow Solids Bioreactor)	$Y_{C,Y2/IN}$
Mass of carbon reporting to Product Y3 (cake-related product stream) as a fraction of that present in influent stream to reactor (U)	kg C(Product Y3)/kg C(Inflow Solids Bioreactor)	$Y_{C,Y3/IN}$
Mass of carbon leaving as CO_2 as a fraction of that present in influent stream to reactor (U)	kg C(CO_2 Respiration)/kg C(Inflow Solids Bioreactor)	$Y_{C,CO2,Solids/IN}$
Mass of carbon reporting to Product Y4 (compost) as a fraction of that present in influent stream to reactor (U)	kg C(Compost)/kg C(Inflow Solids Bioreactor)	$Y_{C,Y4/IN} = 1 - (Y_{C,Y1/IN} + Y_{C,Y2/IN} + Y_{C,Y3/IN} + Y_{C,CO2Solids/IN})$

Table 82: Factors for separator and splitter units in solids bioreactor train

Unit number	Separator description	Relevant parameters	Efficiency symbol
4.2	Crust/Surface Product Recovery	Solids to Bottoms H2 Slurry Solids Contents	eff_{H2} SC_{H2}
4.3	Solid/Liquid Separator	Product Y2 Pressed Cake Solids Contents	eff_{Y2} SC_{H3}
4.4	Product Recovery	Product Y3 Solids Contents: Product Y4	eff_{Y3} SC_{Y4}

7.6 Using the Generic WWBR Flowsheet and Mass Balances

The flowsheets and mass balances presented in this chapter are a springboard for exploring the relevance of the WWBR concept. The generalised WWBR flowsheet in its concise form allows (Figure 21) an appreciation for the WWBR concept to be developed and opens the space for exploring its application into varied situations within the South African context.

The detailed generic flowsheet, presented in four sections (Figure 22, Figure 23, Figure 24 and Figure 25), enables the in-depth consideration of specific options in particular conditions. The factors enumerated in the accompanying tables for each flowsheet reveal the various types of information required. These are sought, first from the literature and subsequently through empirical demonstration, for locations where a WWBR installation is intended. Further, the detailed mass balance equations enable first-order estimations of the efficacy of envisaged scenarios. This is followed through by means of a simulation tool developed as part of a PhD project and presented in Chapter 8. The insights provided by the generalised flowsheets and mass balances perform an important function in assessing the establishment of the WWBR as a new and desirable option and in positioning the concept for future application. This feeds into Chapter 9, South African Wastewater Biorefineries: Conceptual Approach Emerging from this Study.

8 SIMULATION FOR PRELIMINARY EXPLORATION OF POTENTIAL WWBR DESIGN

To pursue the potential for WWBRs in the South Africa industrial and municipal wastewater context, a tool is needed to allow a first-order evaluation of specific opportunities to stimulate future-thinking and assess potential benefit. Thus, a mass balancing tool centred around a generic WWBR flowsheet was developed as part of this project and the PhD of Bernelle Verster. It is intended to serve both as an early-stage feasibility assessment, and as a communication and facilitation tool between potential industry partners, and not a (proprietary) modelling tool.

The flowsheets and mass balances for this approach are presented in Chapter 7 and Appendix F, which list the required factors. In Section 8.1, a range of values is determined from literature for each factor. These values are estimates and can be changed in different model runs depending on the scenario being investigated.

Using data from an extensive literature search, this simulation model is applied with mid-range selected values to provide a set of preliminary mass balances for a particular group of feedstocks, thus providing estimated final outflow values. In Section 8.2, the model is demonstrated across a single bioreactor with values from an experimental study reported in the literature. Section 8.3 reports an integrated WWBR mass balance using municipal wastewater as feedstock.

The model also visualises the flows into the WWBR, between the units and out the WWBR. This numerical and visual presentation of the simulation allows an early-stage evaluation of potential opportunities to resource recovery using the limited information available.

The utility of the model lies in the facility to take the initial simulation and rework the estimations through a number of differing scenarios to explore the consequences of changing the various factors and configurations used. The results of several changes of scenario are reported in Section 8.4 and are used to establish the value of this tool as an initial consideration of application of the WWBR concept to any local setting.

8.1 Selection of Factors for Unit Mass Balances

Considering the generic flowsheets and mass balances presented in Sections 7.1.1 and 7.1.2, it is apparent that any preliminary overview of the options for a WWBR in a particular location requires a set of inflows, bioreactor yields, separation efficiencies and splitter ratios that are reasonable for the conceptualised scenario. The potential inflows and combinations of inflow are determined by the anticipated setting, but estimated ranges for the other factors can be determined from literature for the initial analysis. Although these values are clearly dependent on specific requirements, bioreactor configurations and local conditions, an order of magnitude estimation is useful for preliminary analysis of alternatives.

Where a range of literature values are available, or a single value that is highly optimised for the specific system, a conservative value is applied to take the likely lower yields available from wastewater into account, as well as lower yield values that may be more appropriate for an integrated system as opposed to a maximised value for a single unit system. Where possible, concerns regarding the highest attainable yield values are discussed.

8.1.1 Bacterial bioreactor factors for mass balances

Bacterial growth rates and specific product formation rates vary widely depending on physiological conditions, dominant metabolism and bacterial grouping (Harding, 2009). For example, the energy efficiency of aerobic and anaerobic growth results in differing growth yields and rates. Similarly, the metabolic load of photosynthesis affects yields and rates. Further, metabolite production can be growth-associated or produced during the stationary phase (Doran, 1995). All these factors affect the stoichiometry and rate of production; however, a theoretical mass balance is possible.

The critical factors affecting the bacterial bioreactor were highlighted in Chapter 7 by establishing the material balances around this reactor system. The need for biomass retention in the WWBR bioreactor was presented in Chapter 6 and is recognised to affect the model presented here. Recycling or retaining biomass enables higher apparent biomass concentration, and thereby the rates of metabolism for removing contaminants and producing products. In some cases, biomass retention or recycling may not be feasible – depending in particular on the location of product. For example, where an intracellular bioproduct is produced, the cells need to be broken to recover the product, which renders them unviable.

Bacterial biomass factors

Typical biomass yields for aerobic bacterial processes reside in the range from 0.38 to 0.5 g-biomass per gram organic carbon source where this carbon source is a carbohydrate (Bailey & Ollis, 1986). Higher yields are expected from less oxidised materials such as long chain fatty acids and oils, owing to their lower oxygen content. Harding (2009) provides biomass yields across a range of carbon sources. The bacterial biomass yield produced during PHA production from confectionery wastewater was reported as 0.34 g-biomass/g-substrate COD (Fernández–Dacosta, et al., 2015; Tamis, et al., 2014). This translates to 0.427 g-biomass-C/g-substrate-C, where g-substrate-C is equal to total organic carbon (TOC) (see Section 8.2). The bacterial biomass concentrations obtained during PGA production, reported in Appendix D.2.1, are 4.98 g/ℓ at 37°C and 4.40 g/ℓ at 30°C, which translate to 0.185 and 0.164 g-biomass-C/g-substrate-C, respectively.

The conservative value of 0.164 g biomass C/g substrate C is used in Section 8.3. These values compare reasonably well with the review of PGA production of Madonsela (2013), reporting a biomass concentration in the range of 2-5 g/ℓ. The articles used in the review mainly reported biomass concentrations and not yield, thus it is not possible to calculate exact yield values.

The bacterial biomass composition used in this model is for aerobic growth, $CH_{1.8}O_{0.5}N_{0.2}P_{0.01}$ (Roels, 1983) and the calculations to obtain the mass percent contributions are illustrated in Table 83.

Table 83: Conversion of composition to mass percent for bacterial biomass

Element	**Composition: Normalised to C** (Wu, 2015) (mol element per mol C in molecule)	**Molar Mass of Element** (g/mol element)	**Mass** (g element/mol molecule)	**Biomass Composition** (wt fraction: g/g total dry biomass) **values used in model**
C	1.00	12	12.00	0.480 (TOC bacterial biomass)
N	0.20	14	2.80	0.110
P	0.01	31	0.31	0.012
H	1.80	1	1.80	0.072
O	0.50	16	8.00	0.320
Total	**N/A**	**N/A**	**24.6**	**1.000**

Bacterial bioproducts factors

The production of bacterial bioproducts is usually reported in terms of volumetric concentrations in the form g-product/ℓ-broth. These may be converted to a yield given in terms of g-product/g-substrate, and more specifically, a carbon-based yield given as g-product-C/g-substrate-C fraction for use in the mass balance. Bacterial bioproducts can be intracellular (reside inside the cell) or extracellular (exported to outside of the cell). The location of the product affects the potential of the biomass to be recycled as well as the DSP required. These may have implications on the optimum yields possible, especially in the integrated WWBR.

The reported datasets on bioproduction are mostly generated in shake flask and laboratory experiments, and are thus are not entirely suitable for calculations modelling commercial scale bioreactors. However, the first experimental values for any specific situation will be from this level of experiment, and the resultant values for yields are assumed to be acceptable for a first level approximation.

Intracellular bacterial bioproduct V1

As an example of the literature data required for the modelling of the bacterial bioreactor, production of PHAs from confectionery wastewater containing (7.8 soluble + 0.8 solid) g-COD/ℓ is described. Tamis et al. (2014) performed the experiment, while a techno-economic study was performed using the data. PHAs are a group of biobased biodegradable polymers with wide application, as discussed in Section 5.4.1. PHA production from wastewater is well investigated, especially by using an AGSR (De Bruin, et al., 2004).

One of the most studied of the PHAs is polyhydroxybutyrate (PHB) with the molecular formula $C_4H_6O_2$ and a carbon fraction of 0.56. A case study producing PHB from confectionery wastewater is used as the intracellular bacterial bioproduct to demonstrate the model simulation for a simple bacterial bioreactor train presented in Section 8.2. The carbon-based yields, given as g-product-C/g-substrate-C, are calculated as shown here.

The incoming COD was fermented to VFAs. No significant COD loss was observed in the anaerobic fermentation steps. While the VFA profile consisted of various acids, the greatest fraction was acetic acid (32%) (Tamis, et al., 2014). Hence, in this model it is assumed that all incoming COD is in the form of acetic acid, for simplicity of calculation. Thus:

COD value of 1.07 g-COD/g-acetic acid

(7.8 soluble + 0.8 solid) g-COD/1.07 = 8.04 g-acetic acid/ℓ

C fraction of acetic acid = 0.4

8.04 g-acetic acid/ℓ × 0.4 = 3.21 g-C/ℓ-incoming substrate (= TOC = total carbon)

The overall process yields were 0.34 g-biomass/g-COD, 0.11 g-PHA/g-COD, and 0.55 g-CO_2/g-COD. For the WWBR model used in this project, the TOC yield values of the PHB and biomass are required; thus, these values need to be converted, first to g/ℓ components using the g-COD/g-component values, and then to g-C/ℓ using the carbon composition values.

Table 84 lists the outgoing concentration of the biomass, PHA and CO_2 in g-C/ℓ, based on the specified incoming feed stream, as well as the carbon-based yields that are independent of volumetric flow rate and concentration of the feed stream. These are used in the model. PHA for the purposes of this model is assumed to be composed of PHB only.

Table 84: Carbon yields for PHA, biomass and CO_2 produced from acetic acid

Component	**COD Yield** (g-component/ g-COD-substrate)	g-COD-component/ℓ	g-COD/g-component	g-component/ℓ	**Fraction C** (g-C/g-component)	**Total concentration C-in** component (g-C-component /ℓ)	**Yield** (g-C-component/ g C-substrate)
Substrate content							
Incoming substrate as acetic acid		7.8 + 0.8 = 8.6	1.07	8.040	0.400	3.210	
							Product content
PHB produced	0.11			0.946	0.558	0.528	0.165
Bacterial biomass	0.34			2.924	0.480	1.404	0.437
CO_2 produced	0.55			4.730	0.270	1.277	0.398
Sum		**8.6**		**9.880**		**3.210**	**1.000**

Component	COD Yield (g-component/ g-COD-substrate)	g-COD-component/ℓ	g-COD/g-component	g-component/ℓ	Fraction C (g-C/g-component)	Total concentration C-in component (g-C-component /ℓ)	Yield (g-C-component/ g C-substrate)
Rationale							
Calculation			Fundamental value	= g-COD/ℓ/ g-COD/g-component (CO_2 back-calculated)	Fundamental value	=C-composition × g-component/ℓ (CO_2-C remainder)	g-C-component/ g C-substrate (CO_2-C remainder)
Balance				No need to balance (H, O, N, P not accounted for)		Carbon	Yield

Extracellular bacterial bioproduct V1

PGA is another biopolymer with a variety of applications (Section 5.4.2). It is used here as an example of an extracellular product. A similar approach would be taken for other extracellular products. The production of PGA from wastewater is also the focus of a previous WRC report (Verster, et al., 2014). Subsequent analysis of this extracted and purified γ-PGA showed a γ-PGA suitable for wastewater applications, but not for areas that require a specific composition of high molecular weight stereoisomers. The molecular formula of a PGA monomeric unit is $C_5H_7O_3N$, which translates to $CH_{1.4}O_{0.6}N_{0.2}$, and an elemental composition in terms of a mass percentage C: 0.465, N: 0.109, P: 0.000. It is used in Section 8.3 as the extracellular bioproduct to demonstrate the model using an integrated system.

Reported concentrations for PGA production vary widely, from less than 1 g/ℓ-broth to more than 100 g/ℓ-broth (Madonsela, 2014). Typical substrate compositions reported to date follow a ‘Medium E’ recipe (Birrer et al., 1994). A modified version of this medium was used in this report (Appendix D.1.2) as shown in Table 85, with a maximum PGA concentration of 3.4 g/ℓ obtained at 37°C compared to 6 g/ℓ at 30° (Appendix D.2.2), which translates to 0.123 and 0.216 g-C-product/g C-substrate as shown in Table 85. The conservative value of 0.123 g-C-product/g C-substrate is used in Section 8.3.

Table 85: Carbon yields for PGA and biomass produced from Modified Medium E

Component	g-component/ℓ	Molecular Formula	Fraction C (g-C/g-component)	Total C (g/ℓ)	Yield (g-C-component/ g C substrate)
Substrate content					
Glucose	20	$C_6H_{12}O_6$	0.4	8.0	
Glycerol	1	$C_3H_8O_3$	0.39	0.4	
Citric acid	12	$C_6H_8O_7$	0.375	4.5	
Total g/ℓ	**33**			**12.9**	
Product content					
Biomass produced	5.0, 4.4	$CH_{1.8}O_{0.5}N_{0.2}P_{0.025}$	0.48	2.4, 2.1	0.185, 0.164
PGA produced	3.4, 6	$C_5H_7O_3N$	0.465	1.6, 2.8	0.123, 0.216

Bacterial interim product VFAs

VFAs are generally a mixture of acetic acid (C fraction 0.4), propionic acid (C fraction 0.486) and butyric acid (C fraction 0.545), and are produced as an interim product in the production of PHAs, biogas and hydrogen. VFA production through fermentation is a common way of converting organic material to a more biologically available form for use in, for example, PHB production or algal bioreactors. Fernández-Dacosta et al. (2015) used a yield of 0.91 g-product-COD/g-substrate-COD (translating to 0.97 g-product-C/g-substrate-C). Wijekoon et al. (2011) reported VFA yields at different organic loading rates, translating to g-product-C/g-substrate-C in the range from 0.7 to 0.95.

There is no significant COD loss in the conversion of incoming (complex) COD to VFA. In conventional single unit bioreactor systems, as illustrated in Section 8.2, this VFA is then used to produce biomass and PHA, for example, and the value of exiting VFA is much lower. In this model, the VFA yield is determined by subtracting the product and biomass yield from the VFA yield.

Bacterial respiration factors

Bacterial respiration depends on the solid residence time. For activated sludge wastewater treatment, a higher endogenous respiration rate translates to less sludge production, but also to higher aeration costs. In the WWBR, endogenous respiration should be minimised to allow a greater product yield, but as the only available design value relevant to wastewater, the endogenous respiration rate used in Henze et al. (2008) of 0.24/day is selected for use in the runs of the model reported here.

Summary of yield factors used for Bacterial Bioreactor

The values used in Section 8.3 to demonstrate simulated mass balance for the integrated system, using the extracellular product PGA as hypothetical example are presented in Table 86.

Table 86: Carbon-based yield factors for bacterial bioreactor (Section 7.3.3)

Conversion description	**Symbol of factor**	**Estimated range of factor values in literature** (g C/g C-substrate)	**Selected factor value for start point** (g C/g C-substrate)
Mass of carbon reporting to biomass as a fraction of that present in influent stream to reactor (B)	$Y_{C,XBact/IN}$	0.164-0.185	0.164
Mass of carbon reporting to extracellular Product V1 as a fraction of that present in influent stream to reactor (B)	$Y_{C,V1/IN}$	0.123-0.216	0.123
Mass of carbon reporting to interim product VFA as a fraction of that present in influent stream to reactor (B)	$Y_{C,VFA/IN}$	0.7 to 0.95	$0.7 - Y_{V1/IN} - Y_{C,XBact/IN}$
Mass of carbon leaving as CO_2 as a fraction of that present in influent stream to reactor (B)	$Y_{C,CO2Bact/IN}$	up to 0.24	0.24
Mass of carbon remaining unconverted as a fraction of that present in influent stream to reactor (B)	$Y_{C,INBact,unconverted/IN} = 1 - (Y_{C,XBact/IN} + Y_{C,V1/IN} + Y_{C,VFA/IN} + Y_{C,CO2Bact/IN})$	remainder	remainder

8.1.2 Algal bioreactor factors for mass balances

While this model does not specify the type of algal reactor used, it is noted that most literature on algal production from wastewater has focused on HRAPs or adaptions thereof (Section 3.4.2). The algal reactor is likely to be the main reactor when waste streams, which are high in nitrogen and phosphorous but low in COD, are used. Algal reactors are not likely to be the main reactor where there are spatial constraints, due to the large land requirement. The reactor should be designed to create a selective environment to favour the desired algal growth (Mooij, et al., 2015).

While total COD removal is a factor of residence time and thus of the size of the algal reactor, the total COD removal is reported to be in the order of 31-53% in HRAPs combined with advanced settling ponds (Rose, et al., 2007).

Algal biomass factors

This model makes no assumptions about the specific species present in the bacterial or algal bioreactors. The reactor environment represents a dynamic ecosystem. It is possible to design a selective environment to favour a specific product, rather than an algal species (Mooij, et al., 2015). Algal biomass is not recycled, as higher biomass or nutrient concentration in the almost-compliant effluent is not needed, apart from which the algal cells are generally broken during product recovery and are thus no longer viable.

The biomass concentration in the algal bioreactor is generally not as high as found in conventional algal biorefinery conditions: Typical nitrogen concentrations of 15-20 mg/ℓ in domestic municipal wastewater effluent would stoichiometrically support a microalgae growth density of approximately 0.2 g/ℓ, far lower than the densities achievable in ideal, nutrient-replete conditions, which range from 2 g/ℓ to 10 g/ℓ (Peccia, et al., 2013). The model values for algal biomass ($C_{106}H_{181}O_{46}N_{16}P$) are based on Park et al. (2011), with a carbon fraction of 0.520. In a review of heterotrophic algal cultivation (Bumbak, et al., 2011), biomass yields on different substrates, but most commonly acetate and glucose (with a carbon fraction of 0.407 and 0.4, respectively) ranged from 0.41 to 0.81 g-CDW/g-substrate. Converting into a g-C-biomass/g-C-substrate yields gives a range of 0.524-1.053. The biomass concentration ranged from 30 g/ℓ to 117 g/ℓ, which, using data in Bumbak et al. (2011), (Appendix G.1.2) translates to a C-biomass/C-substrate yield of 0.3-1.1. The biomass content of high lipid producers tended to be lower, and using one example reported in the review, the biomass producing docosahexaenoic acid from ethanol was 83 g/ℓ from 217 g/ℓ, translating to a g-biomass-C/g-substrate-C yield of 0.381.

Algal bioproducts factors

Algal high-value bioproducts W1

In a WWBR approach, the nitrogen should be directed to product, or biomass, rather than lost to the atmosphere by denitrification. Potential products include phycocyanin and antioxidants like astaxanthin. The yield values for these products are expected to be very low, but their production may still be justified through the high price obtainable, and the potential for co-production with commodity products like algal lipids. For example, high-value pigment yields from algae are reported in the range from 0.03-2.9 g/ℓ, with around 0.3 g/ℓ a conservative estimate produced in heterotrophic cultivation using 50 g/ℓ glucose (Bumbak, et al., 2011). Using phycocyanin (carbon fraction 0.68), this translates to a g-product-C/ g-substrate-C yield of 0.010.

Algal lipids W2

Griffiths and Harrison (2009) compared algal lipid productivity in photo-autotrophic cultivations from literature. They found a wide range of reported values ranging from 13% to 31% dry weight for green algae (most being freshwater species), averaging 23%, and an average lipid content of 41% under nitrogen deprivation. Other taxa had a wider range, but with a similar average. Olguín (2012) reports similar values, and a range of 20-50% oil content for heterotrophic cultures, which is more appropriate for wastewater. Bumbak et al. (2011) compared fed-batch heterotrophic cultivations. The example for docosahexaenoic acid was used with a concentration of 11.7 g/ℓ, in a fed-batch culture containing (accumulated) 217 g/ℓ ethanol, complete conversion is assumed. The g-product-C/g-substrate-C yield is then 0.083.

Algal photosynthesis and respiration factors

Addition of carbon dioxide has been shown to enhance algal productivity by about 30% and reducing nitrogen loss through ammonia volatilisation (Park, et al., 2011). At a WWBR facility, the CO_2 from the bacterial bioreactors could be reused by the algal bioreactor, with a low increase in cost. Algal hetero- or mixotrophic growth, meaning growth on dissolved carbon instead of/or in addition to CO_2, respectively, gives 3 to 10 times greater biomass concentrations than autotrophic growth (Dhull, et al., 2014). According to Chojnacka and Marquez-Rocha (2004), biomass is produced from the organic carbon while chemical energy, for example, in the form of lipids, is converted from light energy.

Autotrophic growth results in CO_2 uptake; heterotrophic growth results in CO_2 production; mixotrophic growth showed no appreciable change in CO_2 in work by Kim et al. (2013). The model assumes a ratio of CO_2 uptake proportional to the incoming carbon substrate, which can be altered by the user. The default value is 0.1, or 10% of the incoming g-substrate-C.

Summary of yield factors used for algal bioreactor

The values used in Section 8.3 for the simulated mass balance for the algal bioreactor are presented in Table 87.

Table 87: Carbon-based yield factors for algal bioreactor (Sections 7.3.3; 3.4.3)

Conversion description	**Symbol of factor**	**Range of factor values in literature**	**Selected factor value for start point**
Mass of carbon reporting to algal biomass as a fraction of that present in influent stream to reactor (D)	$Y_{C,XAlgal/IN}$	0.3-1.1	0.345
Mass of carbon reporting to Product W1 as a fraction of that present in influent stream to reactor (D)	$Y_{C,W1/IN}$	0.01-0.098	0.01
Mass of carbon reporting to Product W2 (algal lipids) as a fraction of that present in influent stream to reactor (D)	$Y_{C,W2/IN}$ + $Y_{C,CO2Algal/IN}$	0.042-0.210	0.083
Mass of carbon entering or leaving as CO_2 as a fraction of that present in influent stream to reactor (D)	$Y_{C,CO2Algal/IN}$	Negative to positive	−0.1
Mass of carbon remaining unconverted as a fraction of that present in influent stream to reactor (D)	$Y_{C,INAlgal,unconverted/IN} = 1 – (Y_{C,XAlgal/IN} + Y_{C,W1/IN} + Y_{C,W2/IN})$	Remainder	Remainder

8.1.3 Macrophyte bioreactor factors for mass balances

A macrophyte bioreactor is similar to a constructed wetland from an engineering design perspective, but different from an economic and operating perspective. Because a macrophyte reactor is also aimed at producing a valuable product (in addition to water) the installation and operating costs considered feasible are higher than for a treatment wetland, and the harvesting yields have qualitatively higher required efficiencies. Quantitative values are less well characterised for this reactor in the WWBR, with very little research to date on potential products and their recovery, working in parallel with the remediation function. Section 3.4.3 reviews the factors affecting the macrophyte bioreactor. Here, more than with any of the other reactors, the need for environmental sensitivity in the choice of biological species coincides closely with selecting appropriate product. Using indigenous species is best from a biodiversity point of view; however, the basic research on suitability, productivity, technical performance and market need for products from indigenous species is still needed.

Macrophyte biomass and bioproduct factors

There are high-value bioproducts such as colourants from macrophytes (Bechtold & Mussak, 2010), and potential agricultural-type products that do not use the entire plant, such as fruits and seeds. It may be more suitable to select products that use as high a proportion of biomass as possible, to allow a high ratio of removal of plant matter; thus, fibre for (geo)textiles, composites and the construction industry are considered. While growing food on wetlands is possible (Kakuru, et al., 2013), wetlands used for wastewater treatment may be exposed to contaminants that are hazardous to (human) health. Food products are not considered in this project.

To demonstrate the model, flax (*Linum usitatissimum*) has been chosen as it is well-known, and well characterised. The stem of the plant is used for textile production, and increasingly in building and structural applications, with about 25-30% yields of straw dry mass possible in the final product (Mussig, 2010). For fibre production, the final plant density is about 2000 plants/m^2, and they are harvested before seed production. The main shortcoming of flax production is various environmental issues associated with retting, a step in DSP (Mussig, 2010). Flax grown on treatment wetlands may be suitable, but the manner of harvesting may have to be adapted not to destabilise the rootzone. Although floating wetlands provide access to root harvesting, this may reduce the filtering capacity and microbial activity associated with the root network, which is the principal mechanism of nutrient removal in floating wetlands. Evidence suggests that removing shoots does not affect the roots negatively (Dodkins & Mendzil, 2014b).

Plant fibre compositions are generally reported only in terms of structural polymers – the polysaccharides, cellulose and hemicelluloses, and the aromatic polymer lignin – with little concern for the nitrogen and phosphorous content (Marques, et al., 2010). Flax contains 64% cellulose, 17% hemicellulose and 2% lignin (Bledzki & Gassan, 1999).

Flax contains between 0.56% and 0.91% nitrogen with the green ripe stage showing the highest nitrogen content (Ahmad, et al., 1982). The average value of 0.735% (0.00735) was chosen. The model assumes that the nitrogen content is equal to the nitrogen uptake from the water (no nitrogen fixing from the atmosphere).

For the phosphorous composition, the average value for grasses of 0.23% phosphorous (0.0023) (Harper, et al., 1933) is used, while noting that grasses are higher in nitrogen than flax (2.53%).

For simplicity of calculation, the carbonaceous composition is assumed to be the remainder dry mass ($1 - 0.00735 - 0.0023$), which is composed only of cellulose, with a carbon fraction of 0.444 to give a carbon composition of flax of 0.715.

In general, the largest nutrient removals can be achieved by perennial grasses and legumes that are cut frequently at early stages of growth, but the market value of grass-related products are less well established. Another aspect to consider is that annuals like flax only use part of the growing season for growth and active uptake (WEF FD-16, 2010), with two harvests possible. The model uses an average daily rate.

Macrophyte photosynthesis and respiration factors

Emergent (not completely submerged) macrophytes are considered photoautotrophic, meaning they obtain their CO_2 exclusively from the atmosphere. To estimate the contribution of CO_2-C to the carbon balance, a few assumptions need to be made that cannot be determined at this early stage. These values, which need to be checked again by the user, are summarised in Table 88 and explained below.

Table 88: Estimation of CO_2 uptake of macrophyte bioreactor

Parameter description	Units	Range of factor values in literature/calculation	Selected factor value for start point
1. Estimated kg-C uptake, per harvest (kg-C/m²·harvest):			
Macrophyte biomass per harvest, per m²	kg macrophyte biomass/m² planted area	129.7-2883	0.92
C fraction of macrophyte	kg C/kg macrophyte biomass	0.715	0.715
C uptake	**Ymacrophyte = kg-C/m2 planted area.harvest**	**0.92 × 0.715**	**0.658**
2. Conversion of inflow fluid to planted area-dependent parameter (final unit: m² macrophyte area):			
Incoming liquid to macrophyte reactor (stream F_W in water mass balance)	kg water (and mass balance is set over one day)	Design specific, dependent on mass balance	F_W
Conversion of kg to m³ in model water mass balance (assuming density of 1000 kg/m³)	m³/kg water	1/1000 (assumption)	1/1000

Parameter description	Units	Range of factor values in literature/calculation	Selected factor value for start point
Estimated area of macrophyte bioreactor per m^3 incoming fluid, using a depth of 1.2 m (See Section 8.1.7)	m^2 water/m^3 water	Design specific	0.833
Planted area as fraction of total area	m^2 planted area/m^2 total area of macrophyte bioreactor	0.2-1.0	0.2
Planted area parameter	**F_W × m^2 planted area**	**F_W × 1/1000 × 0.833 × 0.2**	**F_W × 0.000167**
3. Conversion of harvest values to daily value (final unit: /day):			
Harvests per year	/year	0-3	2
Daily average	year/day	1/365 (assumption)	1/365
Harvest average per day	**harvest/day**	**2 × 1/365**	**0.0055**
4. Complete value (kg-C/day)			
$X_{C(G1)}$	**kg-C/m^2 planted area.harvest × F_W × m^2 macrophyte area × harvest/day = kg-C/day**	**0.658 × 0.000167 × F_W × 0.0055**	**0.000000601 × F_W**

The carbon uptake, $Y_{macrophyte}$, is dependent on the planted biomass per square metre of planted surface area in the macrophyte reactor, and the carbon composition of the macrophytes. In this model, the planted surface area is calculated as a function of the water entering the macrophyte reactor, $N_{W(F)}$, in kg/day, and the residence time. The default value of $C_{macrophyte}$ is 0.715 g-C/g-macrophyte-biomass (Section: Macrophyte biomass and bioproduct factors, above).

The above-mat biomass ranges between 0.072 and 2.350 kg/m^2, and root biomass ranges between 0.043 and 0.533 kg/m^2 per growing season (or harvest), with a total mass ranging from 0.130 to 2.88 kg/m^2 (Dodkins & Mendzil, 2014b). For the model, an average total biomass value of 0.920 kg/m^2 was used, calculated from the data in Dodkins and Mendzil (2014b), giving a $Y_{macrophyte}$ value of 0.658 kg-C/m^2·harvest.

Determining the surface area in the model requires an assumption of the depth and the hydraulic residence time of the pond. While this is highly system specific, a default value used for planted wetlands of 1.2 m deep and residence time of one day has been assumed, as used in the water balance (Section 8.1.7). These values can be changed by the user.

The recommended planted area of floating wetlands is 20% of the surface area of the pond, with a higher planted area causing anoxic conditions in the pond. Ponds aimed at nitrogen removal through tightly controlled conditions (either high treatment rate aeration or nitrate removal anaerobic basin) should have 100% cover (Dodkins & Mendzil, 2014b). Using a value of 20% cover gives a heuristic value of F_W × 0.000167 kg·m^2 planted area per day.

Lastly, the carbon uptake over the year needs to be averaged to a daily value to align with the day basis of the mass balance. Two harvests per year are assumed, and the total kilogram plant mass obtained annually is then divided by 365 to give the daily contribution. Using these values, the value of $X_{C(G1)}$ is 0.000000601 × F_W kg-C/day.

Sedimentation in the macrophyte bioreactor

Nutrient uptake through plants accounts for only about 6% of nitrogen and phosphorous removal. Nutrient removal, particularly phosphorous, is mainly done through settling into the sediment, and accounts for about 40-60% of phosphorous (45-75 g/m^2/year (Dodkins & Mendzil, 2014b)). Total nitrogen removal through floating wetlands includes denitrification processes as well and amounts to about 75%.

The model does not make explicit allowance for sedimentation phenomena, but assumes some sedimentation occurs through bacterial (microbial) growth from the remaining unconverted nutrients in the almost-compliant effluent. This is an underestimation, as it does not account for non-biological means of phosphorous deposition, for example. It is an important factor to include in the model, however, because dredging (at a recommended rate of around once every 10 years) is ideal for sustained phosphorous removal (Dodkins & Mendzil, 2014b).

Summary of carbon-based yield factors used for macrophyte bioreactor

The values which will be used in Section 8.3 for the simulated mass balance for the macrophyte bioreactor are presented in Table 89.

Table 89: Carbon-based yield factors for macrophyte bioreactor (Section 7.3.3)

Conversion description	Symbol of factor	Range of factor values in literature	Selected factor value for start point
Mass of carbon reporting to macrophyte biomass as a fraction of that present in influent stream to reactor (F)	$Y_{C,macrophyte}$	Range × 0.81	0.745
Separation efficiency between fibres and cellulosic biomass product streams	eff_{X1}	0.8-1	0.8
Mass of carbon reporting to bacterial biomass committed to sediment, as a fraction of that present in influent stream to reactor (F)	$Y_{C,X,S,Bact/C}$	0.164-0.185	0.164
Mass of carbon entering as CO_2 as a fraction of that present in influent stream to reactor (F)	$CO_{2C,Macrophyte(G6)}$	See Table 88	0.00000068 × F_W
Mass of carbon remaining unconverted as a fraction of that present in influent stream to reactor (U)	$1 - Y_{C,X,S,Bact/C}$	Remainder	1 – 0.164

8.1.4 Solids bioreactor factors for mass balances

The solids bioreactor aims to generate value from the bottoms components generated in the WWBR. Products produced using solid substrate type reactors are commonly reported on a g/kg-dry-substrate basis. While not the sole microbial component, solid substrate bioreactions can be dominated by fungi (Singhania, et al., 2009), and too high moisture levels lead to the unwanted dominance of bacteria. Data on valuable bioproduction using wastewater slurries is virtually non-existent (Susana forum on SSF (Verster, 2016) on faecal sludge in particular), therefore much of this section has not yet been corroborated in the context of the WWBR.

Solids bioreactor biomass factors

Kalogeris et al. (2003) compared the impact of moisture and temperature changes on biomass production in solid substrate bioreactors using wheat straw as substrate. The biomass yields reported range between 28 and 52 g/kg-dry-substrate. The carbon fraction used for wheat straw is based on lignin (using $C_9H_{10}O_2$, carbon fraction 0.72). The same biomass composition as for bacteria was used (carbon fraction 0.47), giving a g-C-biomass/g-C-substrate yield range of 0.019-0.034. A mid-range value of 0.028 was used for the demonstration model.

Solids bioreactor bioproducts factors

The products are separated into three broad categories; crust, liquor and cake-related products. The cake-related products can be split further into compost, and cake-related product that is not compost.

Crust-related bioproduct Y1

The crust-related product category makes allowance for products produced at the air-matrix interface. This may be through fungal fruitbodies (commonly known as mushrooms) or a biofilm, and includes enzymes (Stamets, 1993), surfactants (Das & Mukherjee, 2007) and biopolymers (Wu, et al., 2004).

Producing crust-related products would require that the matrix is not turned to improve mass transfer, which may be more suitable to the conventional sludge drying beds found in wastewater treatment.

PGA yield from SSF is in the range from 36-99 mg product/g-dry-substrate (Madonsela, 2013). Using dairy manure as substrate (carbon fraction 0.45, Patni and Jui (1987)), this translates to 0.037-0.1023 g-product-C/g-substrate-C.

Liquor-related bioproduct Y2

The liquor-related product stream contains products like organic acids. From a review of organic acid production using solid substrates, mainly bagasse, the yield of citric acid was in the range of 70-290 g-product/kg-substrate (Pandey, et al., 2010). The bagasse composition was assumed simplified to cellulose with a carbon fraction of 0.444 producing a g-product-C/g-substrate-C yield range of 0.030-0.136. Prado et al. (2005) report similar values ranging from 0.0.45-0.081 in different reactor configurations. A median value of 0.045 g-product-C/g-substrate-C was used in the demonstration model.

Cake-related bioproduct Y3

Cake-related product together with compost make up the remainder of the solids stream, with a separation coefficient/fractional split set by the user.

The cake-related product stream makes allowance for bioproducts that may be used in applications where compost is not suitable, for example brick-making or packaging material (Arifin & Yusuf, 2013; Corpuscoli, 2016; Ecovative, 2016). The nutrient requirement is less important here, expected to be low, and dependent on the nutrients that remain after the entire WWBR process, but a bulk composition of non-digestible fibre (Pelletier, et al., 2013) may be more appropriate. This product category may include spent support matrix. The composition of product Y3 is based on fungal hyphae, with composition fraction value ranges of nitrogen 0.0042-0.202, phosphorous 0.0026-0.0044 and carbon 0.324-0.372 (Novaes-Ledieu, et al., 1967). The fraction values used for the first simulation are the averages nitrogen 0.0122, phosphorous 0.0035 and carbon 0.348.

Compost Y4

The compost produced does not have a user-set composition, but is dependent on the nutrients that remain after the entire WWBR process. The main fraction is organic matter, and most of the nitrogen and phosphate originates from the primary settlement tank. Compost is the remainder and last product of the WWBR process. Typical composition of compost nutrient values are in the range of 0.5-2% nitrogen, 0.3-1% phosphorous (as P_2O_5) and 84-89% organic matter (Lindsey & Hirt, 1999). Typical compost composition from mushroom waste is in the range of 1.8-3% nitrogen, 0.5-1.4% phosphorus and 33-37% carbon (William, et al., 2001).

Solids bioreactor respiration factors

Sugama and Okazaki (1979) reported that the ratio of mg CO_2 evolved to mg dry mycelia formed by *Aspergillus oryzae* on rice ranged from 0.91 to 1.26 mg CO_2 per mg dry-mycelium. This translates to a CO_2 yield of 0.528-0.731 g-CO_2-C/g-biomass-C. Multiplying with the yield of biomass over substrate used in the model (0.028) gives a g-CO_2-C/g-substrate-C value in the range of 0.015-0.020. The value used in the model is the conservatively higher respiration value of 0.020.

Summary of yield factors used for solids bioreactor

A summary of yield values used as initial estimates to demonstrate the model in an integrated system (Section 8.3) is shown in Table 90.

Table 90: Summary of carbon-based yield values used for solids bioreactor

Conversion description	Symbol of factor	**Range of factor values in literature**	**Selected factor value for start point**
Mass of carbon reporting to biomass as a fraction of that present in influent stream to reactor (U)	$Y_{C,XSolids/IN} = Y_{C,Y4/IN}$	0.019-0.034	0.028
Mass of carbon reporting to product Y1 (Organic Content in Surface/Crust) as a fraction of that present in influent stream to reactor (U)	$Y_{C,Y1/IN}$	0.037-0.1023	0.037
Mass of carbon reporting to product Y2 (liquor-related product stream) as a fraction of that present in influent stream to reactor (U)	$Y_{C,Y2/IN}$	0.030-0.136	0.045
Mass of carbon reporting to product Y3 (cake-related product stream) as a fraction of that present in influent stream to reactor (U)	$Y_{C,Y3/IN}$	0.4	0.4
Mass of carbon lost as CO_2 as a fraction of that present in influent stream to reactor (U)	$Y_{C,CO2,Solids/IN}$	0.015-0.020	0.020
Mass of carbon remaining unconverted as a fraction of that present in influent stream to reactor (U)	$Y_{C,INSolids,unconverted/IN} = 1 - (Y_{C,XSolids/IN} + Y_{C,Y1/IN} + Y_{C,Y2/IN} + Y_{C,Y3/IN} + Y_{C,CO2Solids/IN})$	Remainder	Remainder

8.1.5 Separator efficiency factors

Separators and DSP units are generally well developed and well understood. Obtaining 100% separation between e.g. solids and liquids is possible in bioprocessing, but becomes a cost and time factor. A general compromise is a range of 80-95% separation of solids. General values for separator efficiencies used in bioprocessing are included in Table 91 (Harding, 2009). Where no specific information was available, a product recovery efficiency fraction value of 0.9 was used in the model.

Table 91: Product fractions recovered and waste fractions removed in bioprocessing concentration or purification units (Harding, 2009)

	Solid or product fraction removed*	**Liquid or waste fraction removed***
Adsorption	0.99	0.95
Centrifugation	0.98	0.80
Chromatography	0.99	0.95
Evaporation	1.00	0.90
Filtration	0.95	0.95
Precipitation or crystallisation	1.00	0.00
Solvent extraction and decanting	0.99	0.95
Other	0.99	0.80

Most primary industrial wastewater treatment solids-separation process units operate with clarifiers and flotation devices (Theobald, 2015). Many factors influence the settling characteristics of a given clarifier. Most common factors include temperature variation, short circuits, detention time, weir-overflow rate, surface-loading rate and solids loading, but a yield of 50% reduction in suspended solids is an attainable design goal (range: 50 to 70%). BOD_5 can be reduced from 20% to 40% (Lopez, et al., 2015). Where no further specific information was available, a separation efficiency fraction value of 0.5 was used.

The other important factor in separations is the solids content of the resulting bottoms stream. A solids content of 1% is a common calculation value for primary settling without polymer addition, with values between 4% and 6% commonly required for solids handling, achieved with polymer addition. Typical values for solids contents of slurries found in wastewater treatment are shown in Table 92. A more comprehensive list of solids concentrations relevant to wastewater treatment can be found in "Metcalf and Eddy" *Wastewater Engineering: Treatment Disposal Reuse* (Tchobanoglous, et al., 2003).

Table 92: Representative solids contents of slurries found in wastewater treatment with relevance to WWBR

Type of slurry	Range of solids concentration (fraction dry solids)	Typical solids concentration (fraction dry solids)
PST	0.05-0.09	0.06
Waste-activated sludge with primary settling (similar to the bacterial biomass bottoms)	0.005-0.015	0.008
Waste-activated sludge without primary settling (similar to the bacterial biomass bottoms, without Unit 0.1)	0.008-0.025	0.013
RBC waste sludge (similar to the bacterial biomass bottoms)	0.01-0.03	0.015
Gravity thickener of primary sludge	0.05-0.10	0.08
Aerobic digester of primary sludge	0.025-0.07	0.035
Aerobic digester of primary sludge and waste-activated sludge	0.008-0.025	0.013

Specific considerations and factors relevant to the different reactor unit trains are discussed in the following subsections.

Bacterial bioreactor train separator efficiencies

The separator efficiencies for the bacterial bioreactor are based on the slurries found in wastewater treatment, as these are most closely related to bacterial processes. The values chosen are listed in Table 93.

Table 93: Bacterial bioreactor train separator efficiencies

Unit number	Relevant parameters	Efficiency symbol	Range of factor values in literature	Selected factor value for start point
0.1	Slurry solids content Solids to Bottoms U1	SC_{U1} eff_{U1}	0.01-0.09 design specific	0.06 0.5
1.2	Slurry solids content Solids to Bottoms C2	SC_{C2} eff_{C2}	0.005-0.015 design specific	0.008 0.5
1.3	Slurry solids content Bacterial product recovery Efficiency Solids (Biomass) to Bottoms C3	SC_{C3} eff_{V1} eff_{C3}	0.05-0.10 0.8-1.0 design specific	0.08 0.9 0.5

Algal bioreactor train separator efficiencies

The model does not specify specific DSP options, but does suggest likely recovery methods, thus keeping with the design for DSP approach, which is discussed in the chapter on bacterial bioreactor design (Chapter 6). For primary dewatering, flocculation and sedimentation is suggested, while decanter or spiral plate centrifuges and rotary press are likely secondary dewatering steps. To recover algal lipids, a wet biomass processing route is strongly preferred (Louw, et al., 2016).

In terms of algal product recovery, there are some challenges to consider. Algal cells are larger than bacterial cells, but break fairly easily. In addition, they are too small to filter well. Flotation or skimming is therefore more suited to product recovery. Harvesting at a specific time of day may be advantageous as the algal metabolism changes during the night to include programmed cell death and respiration (Cowan, et al., 2016).

DSP depends on, among other things, the resistance of the algal cells to disruption. The algal process will rely on ecological selection, which is likely to select for a product that fulfils an ecological role, but unlikely to select for easily disrupted cells. While the method of cell disruption lies outside the scope of the model, a conservatively low disruption efficiency fraction value of 0.7 is assumed.

Inglesby et al. (2015) mention using an algal slurry of 20 g/ℓ in an anaerobic digester, which correlates with the representative solids contents of slurries found in wastewater treatment as listed in Table 94.

Table 94: Algal bioreactor train separation efficiencies

Unit number	Relevant parameters	Efficiency symbol	Range of factor values in literature	Selected factor value for start point
2.2	Slurry solids content Solid to Bottoms E2	SC_{E2} eff_{E2}	0.008-0.08 design specific	0.02 0.5
2.3	Algal Bioproduct recovery efficiency Solids (Biomass) to Bottoms E4 Solids to Bottoms E4	eff_{E3} eff_{E4} SC_{E4}	0.8-1.0 design specific 0.008-0.08	0.9 0.5 0.08
2.4	Algal high-value bioproduct recovery efficiency Algal oil recovery efficiency Water content in oil recovery	eff_{W1} eff_{W2} SC_{W2}	0.8-1.0 0.8-1.0 0-0.1	0.9 1 0.05

Macrophyte bioreactor train separator efficiencies

Macrophyte harvesting is likely to occur seasonally, which means the yield values are averaged for daily absorption rates. The almost-compliant effluent moves through the wetland matrix and exits as compliant effluent (stream Z) containing very low levels of solid contaminants. The sediment and macrophytes that constitute the solid fraction (stream G2) remains quite wet, however.

The harvesting is likely to be done manually, or be manually assisted, as large machinery will disturb the wetland matrix, for example, sink the floating wetlands. The bulk of the cellulosic biomass is the fibre in the main portion of the plants, and this is separated from the rootstock through cutting. The remainder rootstock is associated with the sediment (stream G4), and during (probably annual) desludging maintenance, this sediment together with the root mass underneath the floating islands is removed, and either sold as a nutrient-rich soil additive (stream X3) or added to the solids bioreactor (stream U5). It is common practice to remove the rootstock with fibrous plants to achieve longer fibres, but this approach may need to be revised for the WWBR. If this approach is followed, the eff_{G3} value may be higher.

The bulk of the macrophyte is then processed to remove the main fibre sections. The cellulosic biomass product stream (stream X1) that leaves the WWBR system is not completely pure, but has most of the peripheral material, for example leaves, removed. These remnants become the cellulosic biomass, macrophyte bottoms stream (stream G5) that can either be sold as product (stream X2) or be used as support and carbon source in the solids bioreactor (stream U4).

For these reasons, the efficiencies of separation are expected to be quite low. Harvesting of the macrophytes is estimated at a fraction value of 0.8.

The moisture content of flax and hemp fibres are in the range of 10-30% (Kymäläinen & Pasila, 2000), translating to a solids content fraction of 0.7-0.9. The mid-range value of 0.8 was used in the model.

Table 95: Macrophyte bioreactor train separation efficiencies

Unit number	Relevant parameters	Efficiency symbol	Range of factor values in literature	Selected factor value for start point
3.2	Solids to Bottoms G2 Slurry solids contents	eff_{G2} SC_{G2}	unknown 0.008-0.8	0.99 0.6
3.3	Biomass-to-biomass stream efficiency Sediment-to-sediment stream efficiency Slurry solids contents	eff_{G3} eff_{G4} SC_{G3}	0.8-1.0 0.8-1.0 unknown	0.9 0.9 0.6
3.4	Macrophyte fibre recovery Macrophyte fibre solids contents	eff_{X1} SC_{X1}	0.8-1.0 0.7-0.9	0.8 0.8

Solids bioreactor product train separator efficiencies

The solids bioreactor involves two solid-solid separations (Units 4.2 and 4.4) and one solid-liquid separation (Unit 4.3), assumed to be a belt press. While the belt press as a choice for separation in this context has not been corroborated, values for the belt press in the treatment of biosolids have been used (WEF, 2005). Separating the crust-related products is likely to be a cutting or skimming operation with a high yield of crust recovery (eff_{Y1}), but with a fair amount of contaminants in the Y1 stream ($1 - eff_{H2}$). This separation is likely to be similar to an agricultural tilling or scooping operation.

Separating the cake-related product stream (Y3) and the compost (Y4) is likely to be achieved through a (vibrating) sieving action. Efficiency values for this operation are unknown and likely highly specific to the process. Estimates of 60% recovery of product Y3 have been used. Composting proceeds best at a moisture content of 40-60% by weight. At lower moisture levels, microbial activity is limited. At higher levels, the process is likely to become anaerobic and contaminated (Cornell Waste Management Institute, 1996). A mid-range value of 50% solids has been used.

Table 96: Solids bioreactor train separation efficiencies

Unit number	Relevant parameters	Efficiency symbol	Range of factor values in literature	Selected factor value for start point
4.2	Solids to Bottoms H2 Crust to top Slurry solids contents	eff_{H2} eff_{Y1} SC_{H2}	0.8-1.0 0.8-1.0 design specific	0.8 0.9 0.5
4.3	Solids to Bottoms H3 Pressed cake solids contents	eff_{H3} SC_{H3}	0.8-1.0 0.12-0.32	0.9 0.3
4.4	Product Y3 to product stream Product Y4 to product stream Solids contents: Product Y4	eff_{Y3} eff_{Y4} SC_{Y4}	unknown unknown 0.4-0.6	0.6 0.9 0.5

8.1.6 Splitter ratios

The splitters do not have a range of values typically found in literature as their explicit function is to assist the integration of the respective bioreactor units. The impact of the splitters will be briefly illustrated in the contextualisation of an integrated WWBR in Section 8.4. The splitter that directs settled wastewater to the algal bioreactor is informed by the amount of nutrients that is needed to supplement the algal bioreactor stream. It is optional and also dependent on what additional nutrient-rich streams are available (streams D3-D5).

The splitters that send a fraction of potential product as substrate to the solids bioreactor (streams U2-U5) are for providing nutrients or supportive substrate to the solids bioreactor from the WWBR as a source. The defining factor value would be evaluated from the needs of the solids reactor to optimise its productivity, and in the case of the cellulosic biomass, to effect efficient mass and heat transfer. This needs to be traded off with the economic value and market demands of the potential product, and the possibility of alternative substrates to replace the product. The purpose of this model is to assist in investigating these decisions. The selected factor value for the start point is chosen to direct 90% of the flow to the main intended stream, which is indicated by the subscript of the ratio symbol, and summarised in Table 97.

Table 97: Splitter ratios for a generic WWBR

Unit number	Streams split	Ratio symbol	Range of factor values in literature	Selected factor value for start point
0.2	Fraction to Bacterial Bioreactor B1 Fraction to Algal Bioreactor D2	r_{B1} $1 - r_{B1}$	0-1 1-0	0.9 0.1
1.4	Fraction to Bacterial Bioreactor C4 Fraction to Solids Bioreactor U2	r_{C4} $1 - r_{C4}$	0-1 1-0	0.9 0.1
2.5	Fraction to Algal Biomass Stream W3 Fraction to Solids Bioreactor U3	r_{W3} $1 - r_{W3}$	0-1 1-0	0.9 0.1
3.5	Fraction to Cellulosic Product X2 stream Fraction to Solids Bioreactor U4	r_{X2} $1 - r_{X2}$	0-1 1-0	0.9 0.1
3.6	Fraction to Sediment Product X3 stream Fraction to Solids Bioreactor U5	r_{X3} $1 - r_{X3}$	0-1 1-0	0.9 0.1

8.1.7 Water mass balance factors

Because the model is stoichiometric with limited consideration for volumes, an average depth was used to incorporate the surface evaporation per Mℓ water entering the system. Facultative and fermentative ponds, which are mainly populated by bacteria, are between 3 m and 6 m deep. A typical design parameter is 4 m deep, and this value was used for the bacterial reactor. HRAPs are about 30-45 cm deep (0.3-0.45 m), hence the algal reactor was estimated at 0.4 m. Wetlands are typically 1.2 m deep, as this depth is best for maintenance, and shallower ponds promote the growth of *Typha* and *Phragmites*, which is considered a nuisance (Lynda Muller, personal communication, 2015). Floating wetlands may be used in deeper ponds. Duck weed ponds and hyacinth ponds range from 1.5-4.5 m in depth, where non-aerated systems are shallower, and aerated systems deeper (WEF FD-16, 2010, pp. 211-258). The default depth for the macrophyte reactor used in the model is 1.2 m. The solid substrate bioreactor may be closed to aid in increasing temperature in composting, but likely will be open at least some of the time (or total area) to remove excess moisture. A default value of 1 m has been used as a conservative estimate.

The area/volume (m^2/m^3) heuristic was determined by considering a virtual 'block of water', of area dimension $1 \times 1\ m^2$, which then gives a heuristic of area per m^3 unit volume liquid in the reactor, determined by the depth of the reactor, which is effectively = 1/depth.

Table 98: Bioreactor area sizing and evaporation

	Typical depth (m)	Area factor = volume/depth of liquid ($m^3/m = m^2$)	Average annual evaporation (mm)	Average daily evaporation (mm/day)	Volume (m^3) evaporation per m^3 liquid in reactor, per day	Water lost per kg liquid in reactor, per day (kg)
Bacterial bioreactor	6.00	0.17	303	0.8301	0.0001	0.0001
Algal bioreactor	0.50	2.00	303	0.8301	0.0017	0.0017
Macrophyte bioreactor	1.20	0.83	303	0.8301	0.0007	0.0007
Solids bioreactor	1.00	1.00	303	0.8301	0.0008	0.0008

Table 99: Bioreactor area sizing and precipitation

	Typical depth (m)	Area = volume/depth of liquid ($m^3/m = m^2$)	Average annual rainfall (mm)	Average daily rainfall (mm/day)	Volume (m^3) precipitation per m^3 liquid in reactor per day	Water gained per kg liquid in reactor (kg)
Bacterial bioreactor	6.00	0.17	450	1.232	0.0002	0.0002
Algal bioreactor	0.50	2.00	450	1.232	0.0025	0.0025
Macrophyte bioreactor	1.20	0.83	450	1.232	0.0010	0.0010
Solids bioreactor	1.00	1.00	450	1.232	0.0012	0.0012

The default value for annual evaporation used in the model is 303 mm/year (Jovanovic, et al., 2015), while the average annual precipitation used is 450 mm/year (Dedekind, et al., 2016). Note that these are very rough values averaged for the country, and is meant to alert the user to keep these aspects of the water balance in mind. Substituting more accurate values, and investigating scenarios based on seasonal variability may be worthwhile.

From these values, the volume of evaporation lost or precipitation gained can be correlated with the volume liquid in the reactor by multiplying the evaporation or precipitation (kg/kg water in reactor) with the kg water in the reactor. Note that the evaporation and precipitation data needs to be converted to a daily value to fit with the basis of the model. The values are only applied to the bioreactor units and not to other process units, which represents an underestimation.

8.2 Demonstration of Simulation for a Simple Bioreactor Train: PHA from Confectionery Waste

Although many types of wastewater can be used to produce PHA, high concentrations of biologically available COD, relatively low nitrogen, and solid concentrations and low toxicity promote process feasibility. From this perspective, food and paper industry effluents may be considered the most suitable substrates for waste-based PHA production (Tamis, et al., 2014).

The crux of enriching biomass with superior PHA-storing capacity in an open bioreactor system (an environment in which myriad species constantly invade the system for example by being present in the wastewater substrate) is establishing a selective environment. The cyclical presence and absence of VFAs inherent in the AGS-SBR process provides a competitive advantage for PHA-storing species.

8.2.1 Input values for PHB from confectionery wastewater

Fernández-Dacosta et al. (2015) performed a conceptual process design based on data from laboratory- and pilot plant scale operations (Tamis, et al., 2014) using real industrial wastewater from the confectionery industry. They report a PHA yield of 70% dry cell weight, which translates to a g-C-product/g-C-substrate yield of 0.427 as covered in Section 8.1.1: Extracellular bacterial bioproduct V1. The PHA was PHB, which was produced in an aerobic conversion reaction using three sequential fermentation steps with a microbial enrichment culture.

The wastewater from the Mars factory was pretreated in a flotation-based fat separation unit before entering the influent tank of the pilot installation. No primary settlement of solids was employed.

The concentration of ammonium was maintained between 10 and 30 mg N/ℓ at the end of the cycle through dosing after measurement, if necessary. The resulting COD:N mass ratio in the feed stream was approximately 25:1. It was assumed that ammonium was the limiting growth nutrient with other elements required for microbial growth present in excess. In this set-up, the bacterial reactor included a three-step process (refer to Appendix G.2). For the purposes of the model, the three steps are seen as a ‘black box’, with only the overall yield values used. The experiment was run as a fed-batch system. To use the model, an assumption of continuous operation was needed, with a reference value of 1 m^3 incoming, hence analysis over an averaged time period was considered.

The average soluble COD of the wastewater varied strongly over time (intrinsic to factory operation, e.g. semi-periodic cleaning of equipment) with an average concentration of 7.8 ± 4.1 g-COD/ℓ (average ± standard deviation over the dataset) and a concentration of 0.8 ± 0.5 g-COD/ℓ as solids not passing a 0.45 µm pore size filter. The soluble nitrogen concentration in the wastewater was negligible (<1 mg N/ℓ). These values are then incorporated into the model along with the separation and splitter values, as summarised in Table 100.

Table 100: Values for streams in PHA production (adapted from Fernández-Dacosta et al. (2015) and Tamis et al. (2014))

Stream	Value	Comments
B1: Mars candy bar factory	1000 m^3 (unit volume chosen) 3.21 kg-C/m^3 day total	7.8 ± 4.1 g-COD/ℓ soluble 0.8 ± 0.5 g-COD/ℓ solids Assume all COD is acetic acid, 1.07 g COD/g acetic acid
B2: Supplement nutrient stream (urea + PO_4)	0.0041 m^3/m^3 B1 84 g-N/ℓ 9.3 g-P/ℓ 36 g-C/ℓ	See Appendix G.2 The target COD:N mass ratio was around 25:1. A nutrient solution containing 3 M nitrogen in the form of urea, 0.3 M phosphate, 0.3 M $MgSO_4$, 0.2 M K_2SO_4, and trace elements (64 mM $FeCl_3$, 3 mM $ZnSO_4$, 2.7 mM H_3BO_3, 2.1 mM $NiCl_2$, 1.5 mM $CoSO_4$, 0.6 mM $CuSO_4$, 0.8 mM Na_2MoO_4) were provided to the bioreactor.

Table 101: Factors for units in PHA production (adapted from Fernández-Dacosta et al. (2015) and Tamis et al. (2014))

Process Unit	Conversion	Comments
0.1. Separator	$SC_{U1} = 1$ $eff_{U1} = 0$	A solids separator was not used. An initial fat separator was employed, but the data presented reflects the composition after this step, which makes the fat separator fall outside the system boundary.
0.2. Splitter	$r_{B1} = 1$	The entire volume is directed to the bacterial bioreactor.
1.1. Bacterial reactor: biomass	$Y_{C,XBact/IN} = 0.165$	See Table 100.
1.1. Bacterial reactor: Product V1: PHA	$Y_{C,V1/IN} = 0.115$	See Table 100.
1.1. Bacterial reactor: Product: VFA	0	All used up internally, converted to biomass, PHA or CO_2.
1.1. Bacterial reactor: Respiration CO_2	$Y_{C,CO2Bact/IN} = 0.437$	See Table 100.
1.1. Bacterial reactor: Unconverted	0.00	Remainder
1.2. Separator	$eff_{C2} = 0.5$ $SC_{C2} = 0.008$	Assume model default values. Fraction of wastewater to stream D1. "Impurities are about 9% of the solid phase".
1.3 Separator: Centrifugation	$eff_{C3} = 0.9$ $eff_{V1} = 0.95$ $SC_{C3} = 0.08$	Assume model default value for eff_{C3} and SC_{C3}. Disruption efficiency 95%. Final product purity 99.9%.
1.4. Splitter	$r_{C4} = 0$	No biomass is recycled.
Global PHA recovery	0.735	Fraction of PHA in stream I/PHA in stream C1, bacterial broth.

8.2.2 The output values of model demonstration run

Figure 26 shows the carbon mass balance as outlined in Section 8.1 using a Sankey diagram. It visually indicates a large fraction of carbon lost as CO_2, which may be due to a high endogenous respiration rate typical of wastewater treatment. According to the model, 30% of carbon exits through D1, the improved compliance effluent, while the source data assumes that the water is treated well enough for discharge. This may be an artefact of imperfect separations used as default values in the model and requires further optimisation. It highlights the need for additional buffering unit processes, such as the macrophyte bioreactor to improve resilience. Converting the exiting nutrient values into effluent concentration gives 0.0014 kg-C/m^3, 0.00022 kg-N/m^3 and 0.000027 kg-P/m^3, which translate into 1.36 mg C/ℓ, 0.22 mg N/ℓ, and 0.027 mg P/ℓ values that are sufficiently low for discharge.

Sankey diagrams are visual representations of the overall mass balance and show the incoming and outgoing streams as they relate to each other in kg/day. The white areas between the flows are not meaningful, but are merely space to separate the streams for legibility.

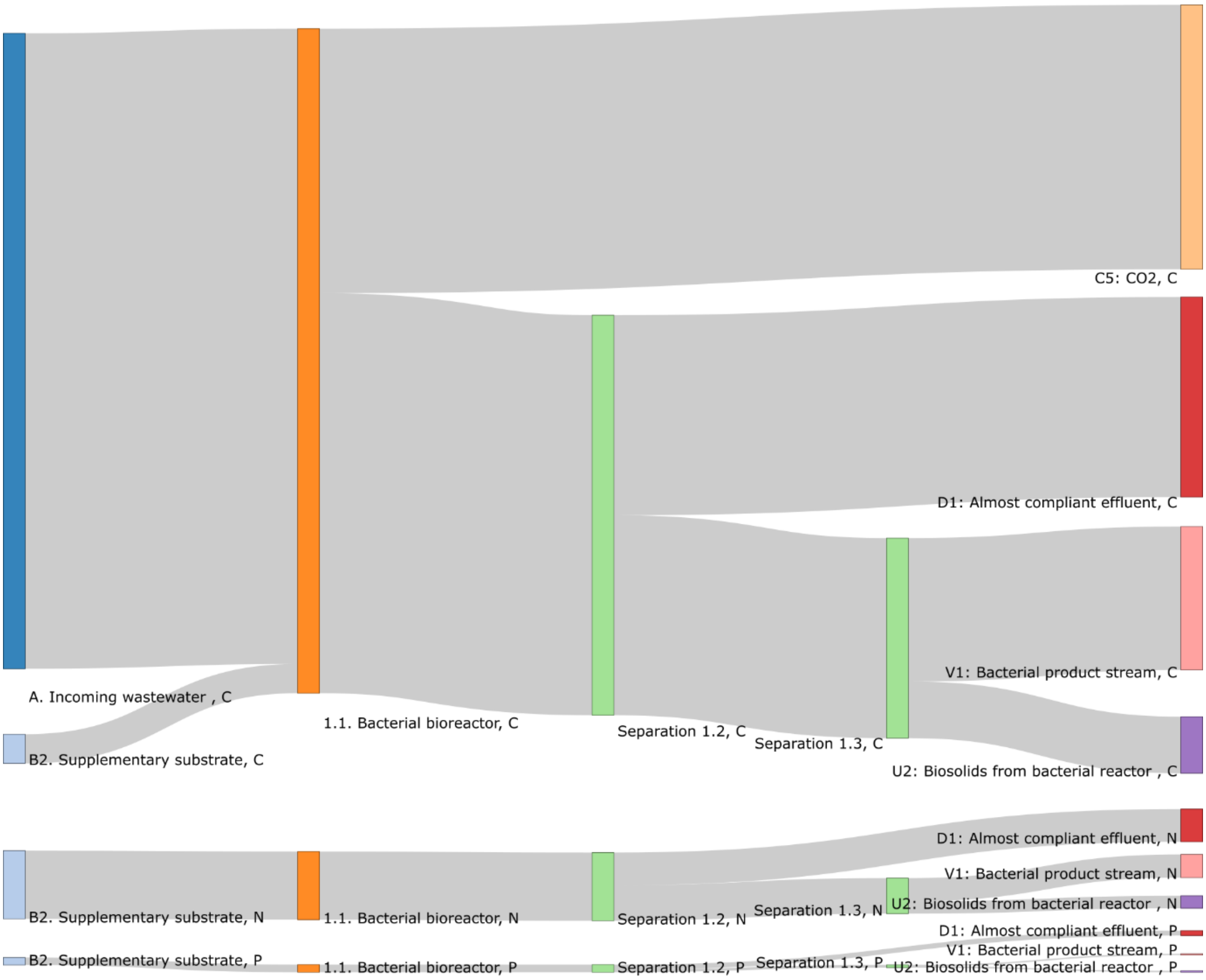


Figure 26: Sankey diagram of carbon, nitrogen and phosphorus mass balances to simulate PHB production in a bacterial bioreactor train using Mars confectionery factory wastewater

The corresponding values for the flows illustrated in Figure 26 are listed in Table 102.

Table 102: Inventory of carbon, nitrogen, phosphorus and water for bacterial bioreactor train using Mars confectionery factory wastewater

Item	Stream Description	C kg/day	N kg/day	P kg/day	W kg/day
Raw, unsettled wastewater A1 to mixing tank	Mars confectionery factory wastewater	3 210	0	0	996 790
Urea supplement stream B2	3 M urea, 0.3 M PO_4	148	344	38	3 570
Incoming (total)		**3 358**	**344**	**38**	**1 000 360**
CO_2 (out)		1 336	0	0	0
Precipitation/evaporation		0	0	0	907
Bacterial product V1 stream (not 100% pure)	PHA	725	117	7	250 575
D1: Improved compliance effluent		1 011	165	25	743 098
U2: Bacterial bottoms		286	62	6.61	6 753

Item	Stream Description	C kg/day	N kg/day	P kg/day	W kg/day
Total outgoing		**3 358**	**344**	**38**	**100 0427**
Difference	*(should be 0)*	0.00	0.00	0.00	839.98
Difference (%)		0.00	0.00	0.00	0.08
Item		**% C of total**	**% N of total**	**% P of total**	**% Water of total**
Raw, unsettled wastewater A1 to mixing tank	Mars confectionery factory wastewater	95.60	0	0	99.64
Urea supplement stream B2	3 M Urea, 0.3 M PO4	4.40	100.00	100.00	0.36
Incoming (total)		100.00	100.00	100.00	100.00
CO_2 (total)		36.99	0.00	0.00	0.00
Precipitation/evaporation		0.00	0.00	0.00	0.09
Bacterial product V1	PHA	21.58	34.01	17.51	25.03
Improved compliance effluent D1		30.10	47.89	65.15	74.28
Bacterial bottoms U2		8.52	18.10	17.34	0.68
Difference	*(should be 0)*	0.00	0.00	0.00	0.00

8.2.3 Concluding remarks on simulating a single unit system

This section demonstrates the use of the model for resource recovery for a single unit system. It also illustrates the format of data reporting in standard metric units of kg and m^3, reporting in terms of elements carbon, nitrogen and phosphorous rather than electrons in the form of COD. The use of elemental compositions is motivated on their direct usefulness in the mass balance; reporting in COD requires an additional assumption about the organic nature of the substrate, whereas TOC values are more useful for this mass balance. The model can be expanded to allow for an electron balance in future.

This section only considers a single unit, the bacterial bioreactor, using the literature study by Fernández-Dacosta et al. (2015), which is not designed for a multi-unit system. This limits the resilience of the system, and the system in its current configuration cannot absorb shock loads of high nutrient-containing waters. It is a suitable system for a highly defined, intensively managed waste stream like food industry's wastewater, but which is less suitable for a complex wastewater. The model is demonstrated for an integrated WWBR in Section 8.3. Some examples of more complex wastewaters are evaluated in Section 8.4.

8.3 Demonstration of Simulation for an Integrated System

The single unit simulated in Section 8.2 is well suited to a stream that is low in nitrogen and phosphorus. For streams that have higher concentrations of nutrients, additional treatment is required. Further additional treatment steps can allow the concomitant meeting of multiple objectives, for example, compliant water, optimised productivity of the major carbon-based product and optimisation of nitrogen- and phosphorous-based products. In this section, a more dilute wastewater with higher concentrations of nitrogen and phosphorous is selected. PGA, an extracellular product, is now the chosen bacterial product. The yields are reduced by 20% to take a possibly non-optimal system and the potential impact of a higher dilution into account, and to allow an interim product like VFA to continue through to the algal bioreactor where algal lipids and a niche product are formed. This may also allow lower residence times within the bacterial bioreactor.

8.3.1 Municipal wastewater as feedstock for integrated WWBR simulation

A hypothetical municipal wastewater stream was used. For the purposes of comparison with the wastewaters used in Section 8.4, the incoming flow was standardised to 1000 m^3 (1 Mℓ). The composition is based on the mid-range average values reported in Henze et al. (2008) and

Tchobanoglous et al. (2003), with data relating to the sludge adapted from Strande et al. (2015). Section 4.2 looks at municipal wastewater as biorefinery feedstock. Appendix C.3 references background data.

The composition values used are shown in Table 103. No supplementary streams were added to optimise the nutrient compositions to demonstrate the integrated unit process.

Table 103: Summary of incoming wastewater values used to demonstrate an integrated multi-unit process

Incoming (Stream A1)	**Total flow** (m^3/day)	**C** (kg/m^3)	**N** (kg/m^3)	**P** (kg/m^3)
Liquid component	1000	0.160 (as TOC)	0.050	0.008
	Solids (kg/m3)	**C** (kg C/kg solids)	**N** (kg C/kg solids)	**P** (kg C/kg solids)
Solids component	0.72	0.583	0.157	0.04

8.3.2 Values of factors for units in the integrated WWBR used in simulation

A summary of the factors used in this demonstration is listed in Table 104 (the biomass composition and product compositions), Table 105 (yield factors) and Table 106 (separator efficiencies). Refer to flowsheets in Chapter 7: Figure 22; Figure 23; Figure 24; and Figure 25.

Table 104: Summary of biomass and product composition values used to demonstrate an integrated multi-unit process

Biomass Composition (g/g total dry biomass)	**C**	**N**	**P**
Bacterial Bioreactor	0.48	0.11	0.013
Algal Bioreactor	0.52	0.092	0.013
Macrophyte Bioreactor	0.715	0.00735	0.0023
Solids Bioreactor	0.47	0.11	0.03
Product Composition (g/g total dry product)	**C**	**N**	**P**
Bacterial Bioproduct V1	0.465	0.109	0
Algal Bioproduct W1	0.68	0.096	0
Algal Bioproduct W2	0.805	0	0
Algal Bioproduct W3	0.52	0.092	0.013
Macrophyte Bioproduct X1	0.715	0.00735	0.0023
Macrophyte Bioproduct X2	0.715	0.00735	0.0023
Macrophyte Bioproduct X3	determined by process	determined by process	determined by process
Solids Bioproduct Y1	0.465	0.109	0
Solids Bioproduct Y2	0.375	0	0
Solids Bioproduct Y3	0.348	0.012	0.0013
Solids Bioproduct Y4	determined by process	determined by process	determined by process
Compliant Effluent Z	determined by process	determined by process	determined by process

Table 105: Summary of outgoing yield values used to demonstrate an integrated multi-unit process

Bioreactor Unit	**Conversion Value (Y)**	
1.1. Bacterial Bioreactor	Biomass: V1: Interim Product VFA: CO_2:	0.164 0.123 0.7 − 0.164 − 0.123 = 0.413 0.24
2.1. Algal Bioreactor	Biomass: W1: W2: W3: CO_2:	0.345 0.01 0.083 (0.345) 0.1

Bioreactor Unit	Conversion Value (Y)	
3.1. Macrophyte Bioreactor	Biomass: X1: X2: X3: CO_2:	0.0000000601 $0.0000000601 \times eff_{X1}$ $0.0000000601 \times (1 - eff_{X1})$ dependent on process -0.0000000601
4.1. Solids Bioreactor	Biomass: Y1: Y2: Y3: Y4: CO_2:	0.028 0.037 0.045 0.4 remainder 0.020

Table 106: Summary of separator and splitter values used to demonstrate an integrated multi-unit process

Process Unit	Conversion Value		Comments
0.1. Separator	SC_{U1} = eff_{U1} =	0.06 0.5	
0.2. Splitter	r_{B1} =	0.9	Assumption: 90% of the overall volume is directed to the bacterial bioreactor, with 10% bypass to the algal bioreactor.
1.2. Separator	SC_{C2} = eff_{C2} =	0.008 0.5	
1.3 Separator: Centrifugation	SC_{C3} = eff_{C3} = eff_{V1} =	0.08 0.9 0.5	
1.4. Splitter	r_{C4} =	0.1	Assumption: 10% of biomass is recycled.
2.2. Separator	SC_{E2} = eff_{E2} =	0.02 0.5	
2.3. Separator: Centrifugation	SC_{E4} = eff_{E3} = eff_{E4} =	0.9 0.5 0.08	
2.4. Separator	eff_{W1} = eff_{W2} = SC_{W2}	0.9 1 0.05	
2.5. Splitter	r_{W3} =	0.9	
3.2. Separator	SC_{G2} = eff_{G2} =	0.6 0.99	
3.3. Separator: Centrifugation	SC_{G3} = eff_{G3} = eff_{G4} =	0.6 0.9 0.9	
3.4. Separator	SC_{X1} = eff_{X1} =	0.8 0.8	
3.5. Splitter	r_{X2} =	0.9	
3.6. Splitter	r_{X3} =	0.9	
4.2. Separator	SC_{Y1} = eff_{Y1} = eff_{H2} =	0.8 0.9 0.5	
4.3. Separator: Centrifugation	SC_{H3} = eff_{H3} =	0.3 0.9	
4.4. Separator	SC_{Y4} = eff_{Y3} = eff_{Y4} =	0.5 0.6 0.9	

8.3.3 Results of applying the values simulating an integrated WWBR

The model output for an integrated flowsheet using four reactor unit trains is summarised in Table 107. The carbon mass balance is visualised in Figure 27.

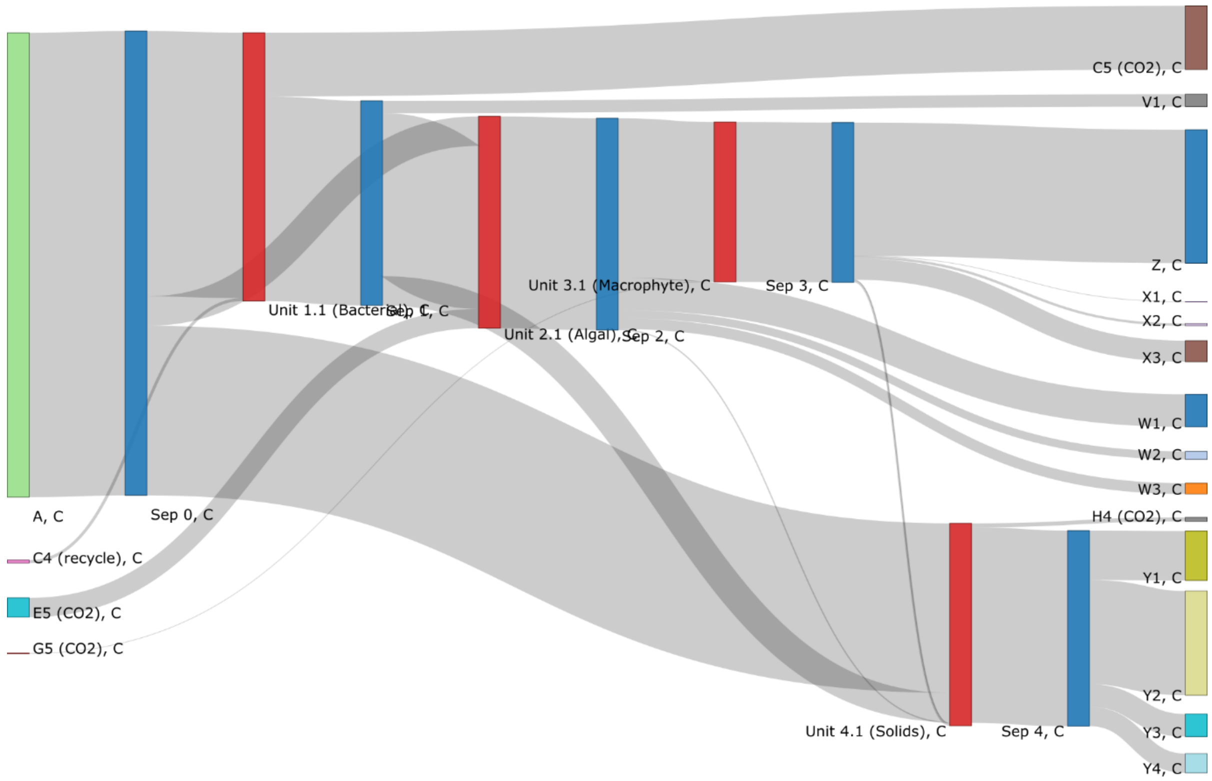


Figure 27: Sankey diagram of the carbon mass balance for the simulation of an integrated WWBR using municipal wastewater as feedstock bacterial product V1, algal high-value product W1, algal lipid product W2, digestible algal biomass W3, macrophyte crust, liquor and cake-related products Y1-Y3, compost Y4. Compliant water

Table 107: Inventory of carbon, nitrogen, phosphorus and water for generic WWBR using municipal wastewater

Item	Stream Description	C kg/day	N kg/day	P kg/day	W kg/day
Raw, unsettled wastewater A1 to mixing tank	Domestic wastewater	580	163	37	999 062
Incoming (total)		580	163	37	999 062
CO_2 (total)		60	0	0	0
Rainfall/evaporation (total)		0	0	0	1 172
Bacterial product V1		15	4	0.40	11 752
Algal bioproduct W1		41	7	1	5 861
Algal oil W2		10	0	0	234
Algal digestible waste W3		13	1	0.07	1
Cellulosic fibre X1		0.42	0	0	0.15
Cellulosic biomass X2		3	1	0.18	0.30
Nitrogen, phosphorous-rich sediment X3		26	6	2	0.05
Crust/surface-related product stream Y1		62	18	8	6
Liquor-related product stream Y2		130	32	1	11 721
Cake-related product stream Y3		28	3	1	53
Compost Y4		24	13	6	274
Compliant effluent Z		166	79	17	970 332
Total outgoing		580	163	37	1 000 234
Difference (should be 0)		0	0	0	0
Difference (%)		0	0	0	0

Item	Stream Description	% C of total	% N of total	% P of total	% Water of total
Raw, unsettled wastewater A1 to mixing tank	Domestic wastewater	100.00	100.00	100.00	100.00
Incoming (total)		100.00	100.00	100.00	100.00
CO_2 (total)		10.32	0.00	0.00	0.00
Rainfall/evaporation (total)		0.00	0.00	0.00	0.12
Bacterial product V1		2.65	2.54	1.10	1.17
Algal bioproduct W1		7.02	4.50	2.90	0.59
Algal oil W2		1.71	0.00	0.00	0.02
Algal digestible waste W3		2.32	0.37	0.20	0.00
Cellulosic fibre X1		0.07	0.00	0.00	0.00
Cellulosic biomass X2		0.52	0.41	0.49	0.00
Nitrogen-, phosphorous-rich sediment X3		4.55	3.65	4.41	0.00
Crust/surface-related product stream Y1		10.64	11.22	22.02	0.00
Liquor-related product stream Y2		22.46	19.43	2.20	1.17
Cake-related product stream Y3		4.88	1.53	2.21	0.01
Compost Y4		4.14	8.12	17.61	0.03
Compliant effluent Z		28.72	48.24	46.85	97.01
Difference (should be 0)		0.00	0.00	0.00	0.00

Even from this early-stage model using the estimate values from Section 8.1, some clear trends are evident. For example, the large difference between algal nutrient removal and macrophyte nutrient removal (averaged to a daily value) indicate that algae may be a better option in intensive production systems for nitrogen and phosphorus removal. Even in this conservative scenario, the potential for the WWBR is significant. While increasing the bioreactor yields is the obvious route to improve productivity, the cumulative effect of imperfect separations have a greater effect overall. This reinforces the need for appropriate bioreactor design targeted specifically at product recovery. In addition, while maximising the productivity of individual reactor units could lead to better economic returns by individual products, the optimisation of overall efficiency of the integrated plant carries higher priority and will yield higher dividends. Further, the combined optimisation of products and water quality are needed through repeated iterations of refinement.

8.3.4 Evaluation of the simulation of an integrated WWBR

It becomes more apparent once the integrated WWBR has been modelled that the combination of a numerical simulation with a visualisation component is a helpful tool. Already at this level of generic experimentation, certain non-intuitive aspects of a scenario emerge together with the confirmation of some more expected outcomes. In Section 8.3, the trialled simulation is repeated using two different wastewaters to further explore both the application of the WWBR concept and the usefulness of the developed simulation tool.

8.4 Contextualisation of an Integrated WWBR for Possible Scenarios

In this section, different wastewaters are compared in terms of their bioproduction potential. The section is concluded by evaluating different realistic separation and yield scenarios to inform future research required on bioproduction in integrated systems.

8.4.1 Comparison of different wastewaters in an Integrated WWBR

The domestic wastewater used to demonstrate the simulation for an integrated system is an example of a complex, dilute wastewater (Section 8.3). Two further examples are given and briefly compared in terms of bioproduction potential per 1000 m^3, using data from Chapter 4. Poultry abattoir waste (Section 4.3.3) is used as the first example representative of complex, more concentrated wastewater. Pulp and paper wastewater is used as an example of a more chemically defined process. These are both industries of high importance in South Africa. Further, they cover the two ends of the spectrum of scale of production: abattoirs are often small scattered industries, while pulp and paper production is covered by four major producers (Section 4.3.1). The wastewater values used are listed in Table 108. The range of reported values indicated in brackets.

Except where noted, the yield, composition and efficiency values used to demonstrate the model (Section 8.3) were used in this section.

Table 108: Summary of incoming wastewater values used to compare an integrated multi-unit process using different wastewaters

Incoming (Stream A1)	Domestic municipal	Poultry abattoir	Pulp and paper
Liquid component, total flow 1000 m^3/day			
C (kg/m^3)	0.160	(1.3-7.5) 4.4	(0.7-1.2) 0.95
N (kg/m^3)	0.050	(0.10-0.25) 0.125	(0.0087 (ammonia) + 0.00152 (nitrate)) 0.00711
P (kg/m^3)	0.008	(0.10-0.25) 0.125	0.004
Solids component			
Solids (kg/m^3)	0.72	(0.2-1.2) 0.7	2.93
C (kg C/kg solids)	0.583	0.61	0.715
N (kg N/kg solids)	0.157	0.041	0.00735
P (kg P/kg solids)	0.04	0.06	0.0023
Reference	Section 8.3	(Molapo, 2009) (Kiepper, et al., 2008)	(Cloete, et al., 2010)
1000 m^3 is equivalent to:	5000 people (population equivalent = 0.2 m3/day)	80 000 birds (fairly large abattoir in South Africa)	11 450 000 A4 sheets (57 tonnes of office print quality 80 gsm paper)

8.4.2 Poultry abattoir wastewater as feedstock for integrated WWBR simulation

The data used for this example is sourced from Molapo (2009) who considered 34 registered and operating high-throughput poultry abattoirs, of which 26 (76.4%) were visited. In February 2006, 322 registered poultry abattoirs (176 high-throughput, 67 low-throughput) and 79 rural abattoirs were recorded.

Abattoir solid wastes include condemned meat organs and carcass, bone, feathers and manure, while the solids settled from wastewater, mainly evisceration waste, and wash waste are transferred in wastewater streams. This wastewater normally passes through screens that remove the larger solids either for treatment or final disposal.

The industry has changed from essentially a number of farm-based operations to large commercial producers where economy of scale in rearing and processing has led to a high degree of operational efficiency. Despite legislation governing the management of waste from poultry abattoirs in South Africa, abattoirs still face serious problems with high volumes of waste, characterised by inadequate disposal technologies leading to environmental and public health implications for nearby communities. Waste material is still not being disposed of properly. Groundwater is being contaminated, air pollution exists and disposal sites are health hazards to scavengers (Molapo, 2009).

Suitable methods to dispose solid wastes include burial, incineration, composting, land application, digestion, animal feed, rendering and landfill, but some of these methods are becoming less feasible due to increasing costs and tighter regulations. Complementing existing practices with the WWBR may ease some of these pressures.

Rendering is used in 46% of the plants interviewed in Molapo's study (2009), creating a high COD malodourous wastewater. A further 8% of plants discharge blood into the municipal system while 35% bury the blood, showing significant potential for a WWBR system to be implemented. Feathers are valuable and not considered as available to the WWBR approach outlined here, although they may contribute to rendering wastes. Research projects targeting value from feather waste are underway in South Africa.

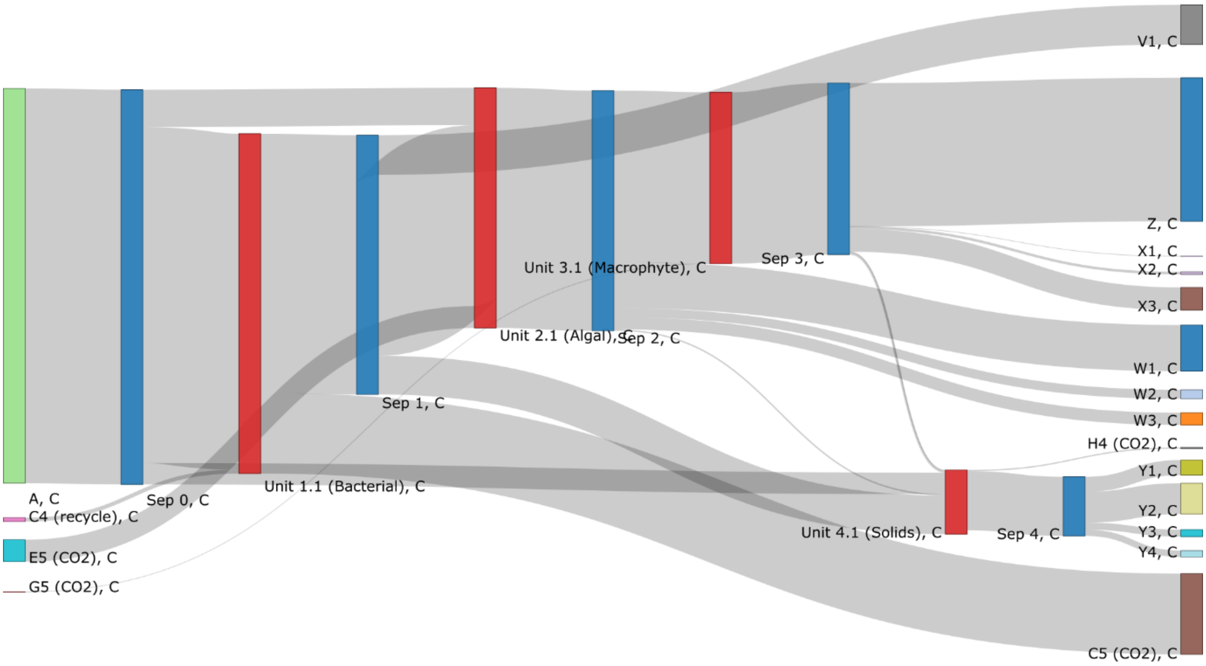


Figure 28: Sankey diagram of the carbon mass balance for the simulation of an integrated WWBR using poultry abattoir wastewater as feedstock, *bacterial product V1, algal high-value product W1, algal lipid product W2, digestible algal biomass W3, macrophyte crust, liquor and cake-related products Y1-Y3, compost Y4, compliant water Z*

Poultry plants today generate a product spectrum including whole birds, cut-up parts, deboned meat and other further processed convenience products, which means the waste generated in processing is now more localised to the abattoir, providing opportunities in innovative integrated waste management.

Poultry abattoirs produce considerable amounts of condemned meat issue, which is rich in proteins and fats, but unsuitable for human consumption. From a discussion with an industry player, the range of waste products have found use in the industry, but manure remains a problem.

Poultry abattoirs use about 15 ℓ to 20 ℓ water per bird, with about 80% to 85% discharged as wastewater. Surface water used for cleaning, and overflow from e.g. scalding tanks seem to be the biggest factors influencing wastewater treatment in the abattoir, at an average value of 25% of the total water consumption each (Molapo, 2009). This, combined with odour- and dust-related air pollution suggest that a macrophyte bioreactor might be a suitable main priority WWBR application in this context, while solids bioreactors may be suitable for manure (Chen, et al., 2005). Indeed, 42% of abattoirs interviewed in Molapo’s study (2009) discharge into a wetland or dam to be used for irrigation.

WWBR in the poultry abattoir context has potential for improved waste management especially in the lower-throughput and rural abattoirs, as well as ‘backyard industries’.

Table 109: Inventory of carbon, nitrogen, phosphorus and water for generic WWBR using poultry abattoir wastewater

Item	Stream Description	C kg/day	N kg/day	P kg/day	W kg/day
Raw, unsettled wastewater A1 to mixing tank	Poultry abattoir wastewater	4 827	154	167	994 650
Incoming (total)		4 827	154	167	994 650
CO_2 (total)		733	0	0	0
Rainfall/evaporation (total)		0	0	0	988
Bacterial product V1		484	14	17	145 763
Algal bioproduct W1		565	65	18	65 065
Algal oil W2		110	0	0	2 594
Algal digestible waste W3		149	7	1	7
Cellulosic fibre X1		0.33	0	0	0.11
Cellulosic biomass X2		31	7	2	0.24
Nitrogen-, phosphorous-rich sediment X3		277	63	17	0.04
Crust/surface-related product stream Y1		183	34	22	18
Liquor-related product stream Y2		378	56	2	19 532
Cake-related product stream Y3		85	6	2	157.27
Compost Y4		78	23	18	812
Compliant effluent Z		1 754	−119	69	761 689
Total outgoing		4 827	154	167	995 632
Difference (should be 0)		0	0	0	0
Difference (%)		0	0	0	0
Item	**Stream Description**	**% C of total**	**% N of total**	**% P of total**	**% Water of total**
Raw, unsettled wastewater A1 to mixing tank	Poultry abattoir wastewater	100.00	100.00	100.00	100.00
Incoming (total)		100.00	100.00	100.00	100.00
CO_2 (total)		15.19	0.00	0.00	0.00
Rainfall/evaporation (total)		0.00	0.00	0.00	0.10
Bacterial product V1		10.03	8.84	9.89	14.64
Algal bioproduct W1		11.70	42.12	10.53	6.54
Algal oil W2		2.28	0.00	0.00	0.26
Algal digestible waste W3		3.09	4.37	0.50	0.00
Cellulosic fibre X1		0.01	0.00	0.00	0.00
Cellulosic biomass X2		0.64	4.53	1.14	0.00
Nitrogen-, phosphorous-rich sediment X3		5.75	40.75	10.23	0.00
Crust/surface-related product stream Y1		3.79	22.13	13.19	0.00
Liquor-related product stream Y2		7.83	36.38	1.32	1.96
Cake-related product stream Y3		1.76	3.64	1.34	0.02
Compost Y4		1.61	14.96	10.54	0.08
Compliant effluent Z		36.33	−77.74	41.34	76.50
Difference (should be 0)		0.00	0.00	0.00	0.00

8.4.3 Paper wastewater as feedstock for integrated WWBR simulation

Paper mill wastewater was chosen separately from pulp because it is more biologically suitable, complex and has more potential for bioremediation to treat, for example, deinking by-products. The solid waste generated in paper mills consists of rejects, deinking sludge, primary sludge and secondary or biological sludge (Bajpai, 2015).

Rejects are impurities and consist of lumps of fibres, staples and metal from ring binders, sand, glass and plastics, and paper constituents as fillers, seizing agents and other chemicals. Rejects also have a relatively low moisture content, significant heating values, are easily dewatered and are, generally, incinerated or disposed of in landfills. Screen rejects have a high content of cellulose fibre.

Deinking sludge contains mainly short fibres or fines, coatings, fillers, ink particles (a potential source of heavy metals), extractive substances and deinking additives. It is normally reused in other industries (e.g. cement, ceramics), or is incinerated, even though it has a poor heating value. Deinking sludge is generated during recycling of paper (except for packaging production). Separation between ink and fibres is driven by a flotation process. The generated deinking sludge contains minerals, ink and cellulose fibres (which are too small to be withheld by filters). This stream is expected to be suitable for PGA production in the bacterial bioreactor.

Primary sludge is generated in the clarification of process water. The sludge consists of mostly fines and fillers and it is relatively easy to dewater. This sludge can be reincorporated into the process for board industry.

Secondary or biological sludge is generated in the clarifier of the biological units of the wastewater treatment. It is either recycled to the product (board industry) or thickened, dewatered and then incinerated or disposed of in landfills. Secondary sludge volumes are lower than those corresponding to the primary sludge. Secondary sludges are often difficult to handle (due to a high microbial protein content). These solids need to be mixed with primary sludge to permit adequate dewatering.

About 40-50 kg of dry sludge is generated to produce 1 tonne of paper at a paper mill; of that, approximately 70% is primary sludge and 30% secondary sludge (Bajpai, 2015). Based on the estimates of 50 kg of dry sludge per tonne of paper produced, and the production of 57 tonnes of paper per 1000 m^3 of wastewater, a solids concentration of 2.94 kg/m^3 can be calculated. It is assumed that fibre is the only component of the solids fraction. Its composition was estimated based on that of macrophyte biomass N: 0.00735, P: 0.0023 and C: 0.715.

The inventory of carbon, nitrogen, phosphorous and water through the integrated WWBR processing paper wastewater is given in Table 110. A quarter of the incoming carbon remains in the complaint water with the remainder distributed to macrophyte products (37%), algal products (11%), bacterial products (5%) and compost (5%). As can be seen, the default yield values produce a deficit in the nitrogen and phosphorous streams due to the low nutrient content in the paper mill wastewater, and the inability of the model in its current format to adjust for nutrient limitation.

Table 110: Inventory of carbon, nitrogen, phosphorus and water for generic WWBR using paper mill wastewater using default values

Item	Stream Description	C kg/day	N kg/day	P kg/day	W kg/day
Raw, unsettled wastewater A1 to mixing tank	Paper mill Wastewater	3 045	29	11	996 109
Incoming (total)		3 045	29	11	996 109
CO_2 (total)		325	0	0	0
Rainfall/evaporation (total)		0	0	0	1 073
Bacterial product V1		131	9	0	62 380
Algal bioproduct W1		227	31	4	29 823
Algal oil W2		50	0	0	1 189
Algal digestible waste W3		68	3	0.38	3
Cellulosic fibre X1		0.37	0	0	0.13

Item	Stream Description	C kg/day	N kg/day	P kg/day	W kg/day
Cellulosic biomass X2		15	3	1	0.27
Nitrogen-, phosphorous-rich sediment X3		131	30	8	0.04
Crust/surface-related product stream Y1		320	19	6	31
Liquor-related product stream Y2		671	26	1	48 280
Cake-related product stream Y3		147	6	1	275
Compost Y4		128	5	5	1 422
Compliant effluent Z		831	−103	−16	853 778
Total outgoing		3 045	29	11	997 182
Difference (should be 0)		0	0.01	0	0
Difference (%)		0	0.02	0	0
Item	**Stream Description**	**% C of total**	**% N of total**	**% P of total**	**% Water of total**
Raw, unsettled wastewater A1 to mixing tank	Paper mill Wastewater	100.00	100.00	100.00	100.00
Incoming (total)		100.00	100.00	100.00	100.00
CO_2 (total)		10.67	0.00	0.00	0.00
Rainfall/evaporation (total)		0.00	0.00	0.00	0.11
Bacterial product V1		4.31	32.40	0.81	6.26
Algal bioproduct W1		7.45	108.15	41.50	2.99
Algal oil W2		1.65	0.00	0.00	0.12
Algal digestible waste W3		2.24	10.74	3.54	0.00
Cellulosic fibre X1		0.01	0.01	0.01	0.00
Cellulosic biomass X2		0.48	11.51	8.37	0.00
Nitrogen-, phosphorous-rich sediment X3		4.32	103.59	75.34	0.00
Crust/surface-related product stream Y1		10.51	67.24	58.07	0.00
Liquor-related product stream Y2		22.02	91.84	5.81	4.84
Cake-related product stream Y3		4.84	19.49	9.27	0.03
Compost Y4		4.21	15.91	43.00	0.14
Compliant effluent Z		27.28	−360.89	−145.72	85.62
Difference (should be 0)		0.00	0.00	0.00	0.00

To eliminate the nutrient limitation (nitrogen and phosphorous), the yield values for bacterial biomass and product V1 were required to be reduced by a factor of 8, as indicated in Table 111. No adjustments to the other units were made, but it is likely that the algal bioreactor would be omitted altogether in this scenario, and the VFA interim product directed to methane through anaerobic digestion. The resulting inventory is shown in Table 112. The carbon mass balance is visualised in Figure 29. These demonstrate the major importance of the macrophyte products for this wastewater processing system.

Table 111: Summary of revised yield values used in generic WWBR for paper mill wastewater

Bioreactor Unit	Conversion Value (Y)	
1.1. Bacterial Bioreactor	Biomass: V1: Interim Product VFA: CO_2:	0.021 0.015 0.7 − 0.021 − 0.015 = 0.664 0.24
2.1. Algal Bioreactor	Not used, splitter 0.2 directs all flow to B1	$r_{B1} = 1$
3.1. Macrophyte Bioreactor	Biomass: X1: X2: X3: CO_2:	0.0000000601 0.0000000601 × eff_{X1} 0.0000000601 × (1 − eff_{X1}) dependent on process -0.0000000601

Bioreactor Unit	Conversion Value (Y)	
4.1. Solids Bioreactor	Biomass: Y1: Y2: Y3: Y4: CO_2:	0.028 0.037 0.045 0.4 remainder 0.020

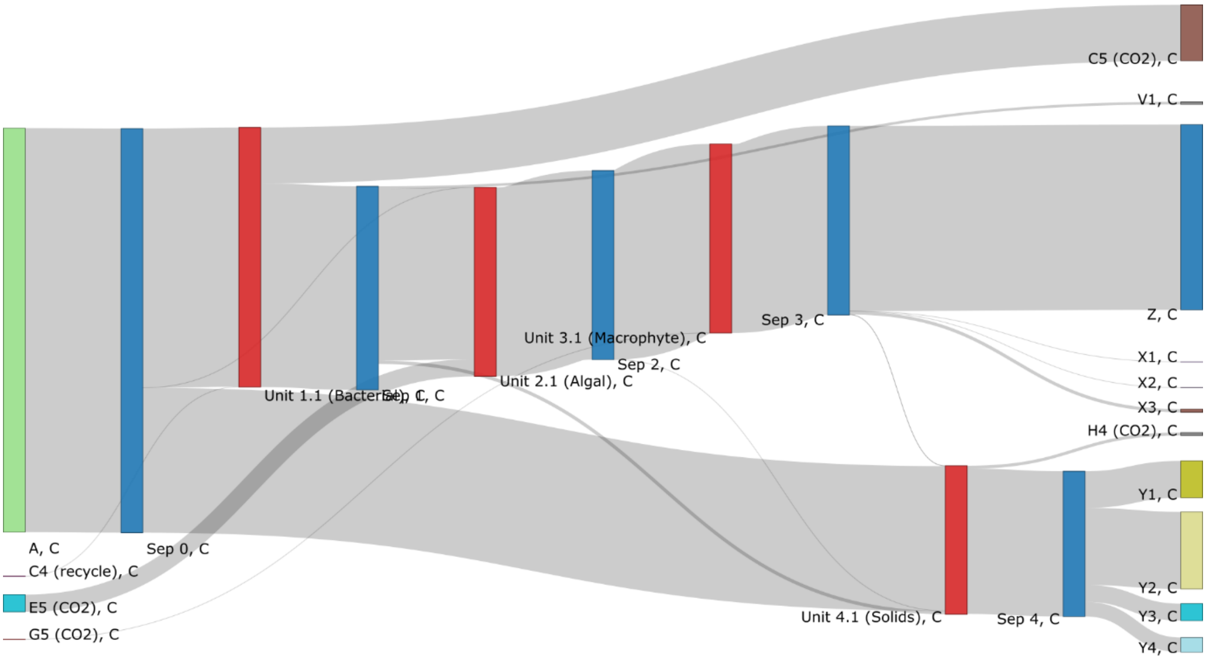


Figure 29: Sankey diagram of the carbon mass balance for the simulation of an integrated WWBR using paper mill wastewater as feedstock and revised yield values, *bacterial* product V1, *algal* high-value product W1, *algal* lipid product W2, *digestible* algal biomass W3, *macrophyte* crust, liquor and cake-related products Y1-Y3, *compost* Y4, *compliant* water Z

Table 112: Inventory of carbon, nitrogen, phosphorus and water for generic WWBR using paper mill wastewater using revised values

Item	Stream Description	C kg/day	N kg/day	P kg/day	W kg/day
Raw, unsettled wastewater A1 to mixing tank	Paper mill Wastewater	3 045	29	11	996 109
Incoming (total)		3 045	29	11	996 109
CO_2 (total)		444	0	0	0
Rainfall/evaporation (total)		0	0	0	1 154
Bacterial product V1		19	2	0.16	7 797
Algal bioproduct W1		0	0	0	0
Algal oil W2		0	0	0	0
Algal digestible waste W3		0	0	0	0
Cellulosic fibre X1		0.40	0	0	0.14
Cellulosic biomass X2		3	1	0.16	0.30
Nitrogen-, phosphorous-rich sediment X3		24	5	1	0.05
Crust/surface-related product stream Y1		276	8	2	27
Liquor-related product stream Y2		581	8	0.24	44 939
Cake-related product stream Y3		127	4	1	238
Compost Y4		110	-3	2	1 229
Compliant effluent Z		1 395	4	4	943 0339
Total outgoing		2 979	29	11	997 2639

Item	Stream Description	C kg/day	N kg/day	P kg/day	W kg/day
Difference (should be 0)		66	0	0	0
Difference (%)		2.16	0	0.01	0
Item	**Stream Description**	**% C of total**	**% N of total**	**% P of total**	**% W of total**
Raw, unsettled wastewater A1 to mixing tank	Paper mill Wastewater	100.00	100.00	100.00	100.00
Incoming (total)		100.00	100.00	100.00	100.00
CO_2 (total)		14.90	0.00	0.00	0.00
Rainfall/Evaporation (total)		0.00	0.00	0.00	0.12
Bacterial product V1		0.65	7.46	1.51	0.78
Algal bioproduct W1		0.00	0.00	0.00	0.00
Algal oil W2		0.00	0.00	0.00	0.00
Algal digestible waste W3		0.00	0.00	0.00	0.00
Cellulosic fibre X1		0.01	0.01	0.01	0.00
Cellulosic biomass X2		0.09	2.07	1.50	0.00
Nitrogen-, phosphorous-rich sediment X3		0.79	18.58	13.51	0.00
Crust/surface-related product stream Y1		9.28	29.16	22.01	0.00
Liquor-related product stream Y2		19.50	27.03	2.20	4.51
Cake-related product stream Y3		4.27	13.95	5.48	0.02
Compost Y4		3.68	-11.18	14.33	0.12
Compliant effluent Z		46.83	12.92	39.43	94.56
Difference (should be 0)		0.00	0.00	0.00	0.00

Pulp and paper wastes are very low in nitrogen and phosphorous. There is some potential for bioproducts to improve the production processes, for example, the deinking process, but due to the high carbon content and the high energy requirements of the industry, energy-generating activities through incineration and anaerobic digestion are suggested. In this case study, focus on macrophyte production has been used to overcome the nutrient shortage.

Further, while final polishing through macrophyte bioreactors may be achieved as well, irrigation to plantations on-site for specialty paper (public relation and marketing uses) may be an option and may provide their fertilisation.

PGA is proposed as a suitable WWBR product in this application to be used in-house for heavy metals removal, flocculation, or deinking agent. Its production may be considered using the bacterial production unit or SSF.

8.4.4 Remarks on using different wastewaters in an integrated WWBR

The total products produced by the three wastewater processes investigated are summarised per 1000 m^3 in Table 113 and visually compared in a bar graph in Figure 30. In addition, the values have been normalised to 1000 kg-C/day incoming, as summarised in Table 114 and Figure 31. While these values are not directly comparable due to the widely differing incoming nutrient loads, it does give an indication of the potential of each wastewater stream. The values were determined by dividing the total carbon of the product by the carbon fraction, with the exception of the sediment product X3 and compost product Y4, which was estimated by adding the carbon, nitrogen, phosphorous and water amounts, as the composition of these are dependent on the process.

From these graphs, it can be seen that streams with a higher nutrient (nitrogen and phosphorous) content are more suitable to bacterial and algal production. Carbon-rich streams are well suited to energy products.

Table 113: Comparison of total amount of each product produced by three wastewater streams investigated, per 1000 m^3 incoming wastewater

kg/day	Domestic municipal wastewater	Poultry wastewater	Paper mill wastewater
Bacterial product V1	33	1 042	41
Algal bioproduct W1	60	831	0
Algal oil W2	12	137	0
Algal digestible waste W3	26	287	0
Cellulosic fibre X1	1	0	1
Cellulosic biomass X2	4	43	4
Nitrogen-, phosphorous-rich sediment X3 *	34	357	30
Crust/surface-related product stream Y1	133	393	594
Liquor-related product stream Y2	347	1 007	1 549
Cake-related product stream Y3	81	244	365
Compost Y4 *	318	930	1 337
Compliant effluent Z C (mg/ℓ)	0.172	2.302	1.479
Compliant effluent Z N (mg/ℓ)	0.081	-0.157	0.004
Compliant effluent Z P (mg/ℓ)	0.018	0.091	0.004

* estimated through mass balance

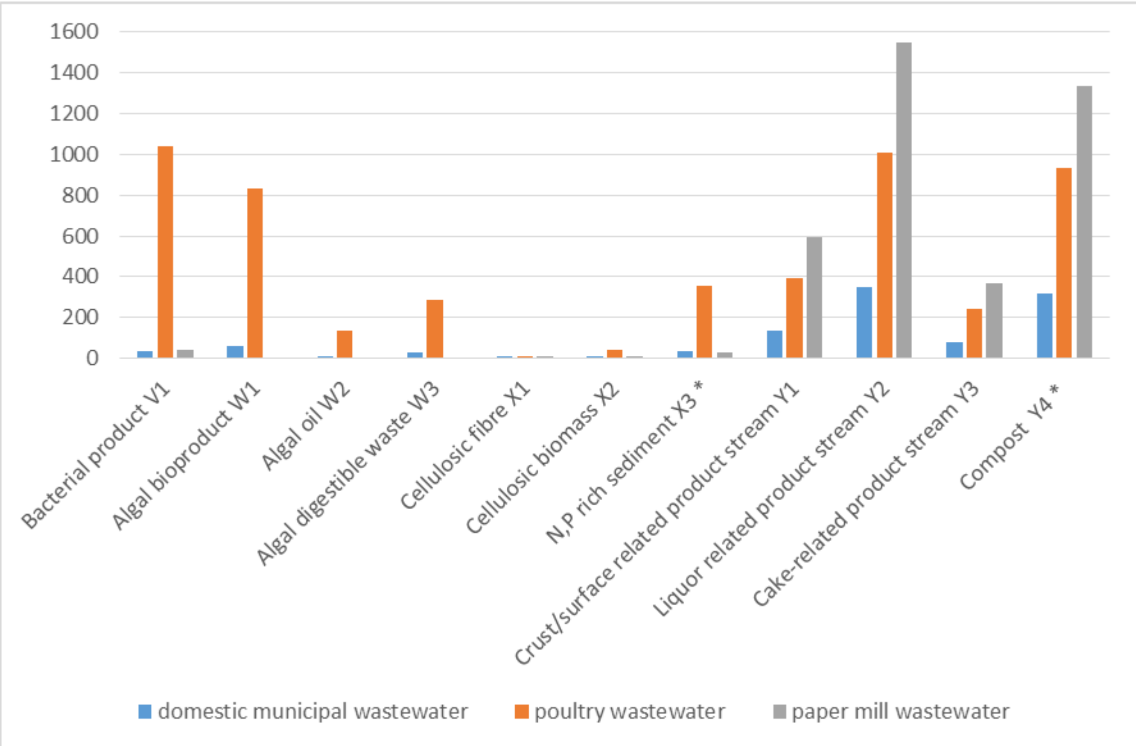


Figure 30: Bar graph comparing total amounts of products produced (kg/day) by each wastewater stream investigated, per 1000 m^3/day incoming wastewater

Table 114: Comparison of total amount of each product produced by three wastewater streams investigated, per 1000 kg C/day

kg/day	Domestic municipal wastewater	Poultry wastewater	Paper mill wastewater
Bacterial product V1	57	216	14
Algal bioproduct W1	103	172	0
Algal oil W2	21	28	0
Algal digestible waste W3	45	59	0
Cellulosic fibre X1	1	0	0
Cellulosic biomass X2	7	9	1
Nitrogen-, phosphorous-rich sediment X3 *	59	74	10
Crust/surface-related product stream Y1	229	81	195
Liquor-related product stream Y2	599	209	509
Cake-related product stream Y3	140	51	120
Compost Y4 *	548	193	440

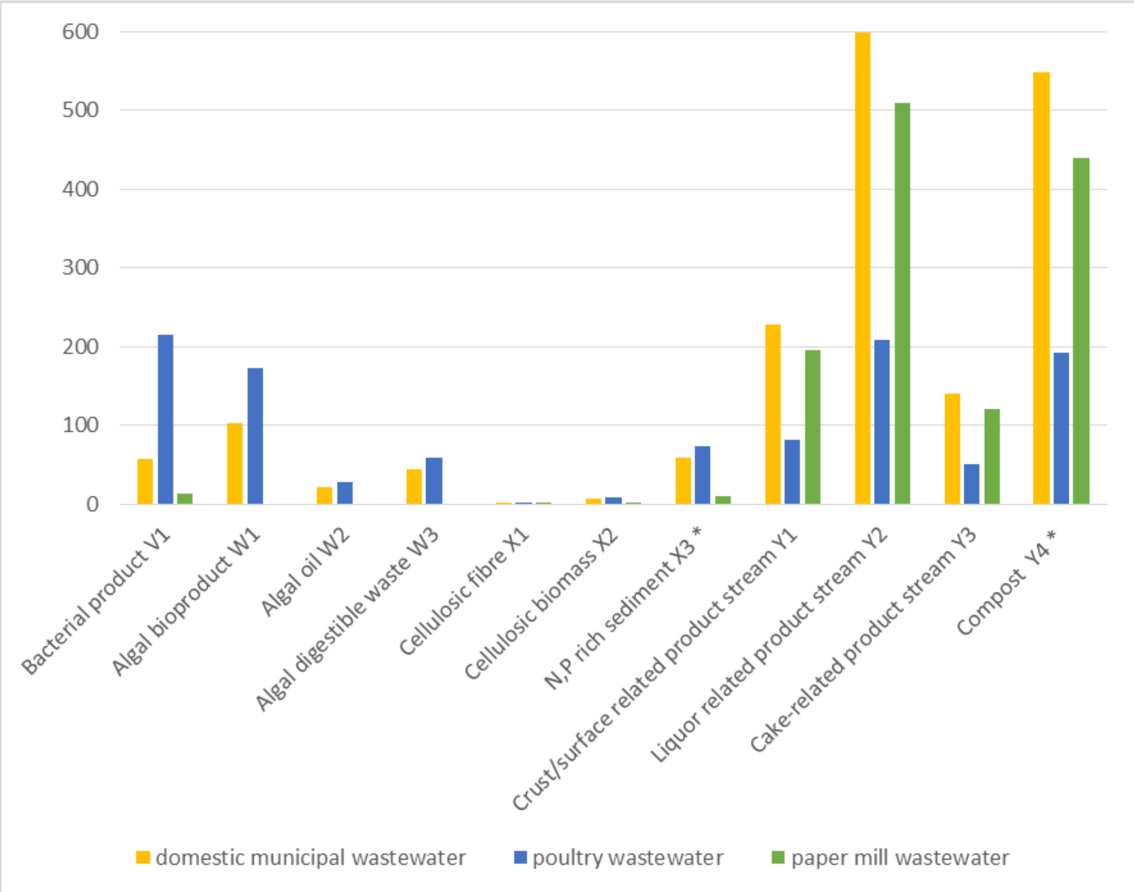


Figure 31: Bar graph comparing total amounts of products produced by each wastewater stream investigated, per 1000 kg C/day incoming substrate

8.5 Future Evaluation of Potential Wastewater Biorefineries

Building on the material balance tool set up in Chapter 7 to describe the integrated WWBR flowsheet, the model has been populated with appropriate yields, conversion factors and separation factors across the unit operations included. This has been done by drawing on literature values as well as prior work carried out within the CeBER at UCT that focused on techno-economic studies and environmental assessment studies, both requiring effective material balance inventories. In all cases, conservative estimates have been made.

Using the calibrated material balance tool, both the unit operations individually and the integrated process can be analysed in terms of the partitioning of incoming carbon, nitrogen and phosphorous to the product range of bacterial commodities such as biopolymers, algal products and macrophyte products, as well as compliant water. This nutrient partitioning has been visualised using Sankey diagrams, which show the potential of the tool.

In the final stage of the chapter, an initial assessment of different scenarios has been carried out by modelling the generic flowsheet containing a bacterial biopolymer reactor, algal reactor, macrophyte reactor and fungal solids reactor. Three differing substrates of varying complexity and nitrogen availability have been investigated. Here the importance of nitrogen for partitioning of carbon to the higher value products has been identified, setting the scene for the ongoing scenario analysis to inform target setting for WWBRs.

9 SOUTH AFRICAN WASTEWATER BIOREFINERIES: CONCEPTUAL APPROACH EMERGING FROM THIS STUDY

Wastewater treatment works are faced with increasing economic and environmental pressure, which provides incentive for increased efficiency. This efficiency has largely focused on improved energy efficiency, but improved knowledge about engineering design and the biology involved in nutrient removal has opened up possibilities for efficiency in the nutrient resource cycle to which wastewater contributes to as well. The potential, in kilogram carbon, nitrogen and phosphorus as raw material for resource recovery from wastewater is massive. Cumulatively, on record there are 12 750 tonnes of carbon, 325 tonnes of nitrogen and 77 tonnes of phosphorus in the wastewater that is released in South Africa every day (Section 4.1.3). This potential was explored in the previous chapter, which investigated different scenarios of utilising wastewater in a WWBR context.

9.1 The WWBR Arena

While reducing the amount of resources ending up in waste streams and reducing the amount of water directed to waste streams is of paramount importance, the potential of WWBR for reducing the losses in both areas is clear. Even in a future where nutrient and water resources are well managed, WWBR still has a critical role as a link in the ecosystem to close the nutrient cycles in an integrated system. A SWOT analysis for WWBR is shown in Table 115.

Table 115: SWOT analysis of WWBRs (adapted from the IEA Bioenergy Task 42 Biorefinery (Fava, et al., 2012))

Strengths of WWBR	**Weaknesses of WWBR**
• Diversified revenue from wastewater. • Contribution to environmental bioremediation of wastewater. • Contribution to closing energy and material cycles. • Economic incentive to improve overall efficiency. • Production of a spectrum of biobased products (food, feed, materials, chemicals) and bioenergy (fuels, power and/or heat) feeding the full biobased economy. • A bridge between, and building on, agriculture, food, and forestry industries. • An alternative to land use for bioproducts (food-feed-fuels nexus).	• Broad, undefined and unclassified area requiring an integrated approach, while being highly site-specific, difficult to work with. • Variable volume, quality, concentration, energy density and composition of water feedstock. • Poor reporting on effluent composition. • Multi-dimensional stakeholder engagement required. • Developing in parallel to bioeconomy: uncertainty about market trends for new and existing products.
Opportunities that could allow growth in WWBR as an industry platform	**Threats to WWBR**
• International consensus that water availability is limited so that the raw materials should be used as efficiently as possible – i.e. development of multipurpose biorefineries in a framework of scarce raw materials and energy. • Strengthening of the economic position of various market sectors (e.g. agriculture, forestry, chemical and energy) due to increased income from products as well as reduced costs due to waste management. • The technology focus on using dilute raw material effectively and an explicit focus on appropriate reactor design for product recovery can contribute to the development of a portfolio of possible products not previously economically feasible (e.g. PGA-related products).	• Inability to cross disciplinary divides to build appropriate skill sets. • Economic and political instability affecting priority of exploring the WWBR concept. • Products from wastewater may have a low market pull. • High investment capital for pilot and demo projects. • Unfavourable implementation and interpretation of regulations at a local level. • Changing water use due to e.g. climate change; water scarcity creates uncertainty about raw material inputs.

9.1.1 Interrelating challenges

The main challenge in a WWBR is the diverse and indefinite nature of the wastewater entering the system. There are several ways to embrace this complexity, for example, pretreating water, which may include digestion or some form of sterilisation, and dosing with supplementary substrate to complement and improve the wastewater composition, but this also adds complexity and cost to the process. Where possible, this should be limited to substrates sourced in close proximity to the WWBR. Fundamentally, the most critical aspect is appropriate bioreactor design.

A secondary challenge is the potentially competing objectives of producing a regulation compliant effluent “water as product”, as well as other economically valuable products. Resource recovery is gaining interest globally; however, and is recognised to improve the operational efficiency of waste treatment facilities in addition to producing products of value. Considerate plant management is key to the success of the WWBR along with appropriate regulation and its interpretation, buy-in from stakeholders like upstream wastewater generators, government and members of the public potentially affected by the effective industrialisation of wastewater.

These two challenges interrelate. While the technologies to address aspects of bioprocessing, wastewater treatment and resource recovery already exist in isolation, little knowledge is yet available about how they integrate, and little to no commercial scale integration exists. The feasibility model demonstrated in Chapter 8 facilitates early-stage investigation into the interaction of different bioreactors. The next step is to test the assumptions inherent in the model at laboratory and pilot scale.

9.1.2 Industry players

Industrial wastewaters may already be utilised to improve water and energy efficiency where feasible, and this may create an opportunity cost to implement a WWBR. In contrast, the perceived effort and a lack of the trust required to build industrial ecologies to create WWBRs may negatively affect moving forward. However, there are some industry players who are already open to investigation of resource recovery or even more fundamental biorefinery concepts. The attractiveness may lie in a combination of factors, such as biologically suitable waste streams, problematic waste streams, an innovative industry culture, particularly a desire to be part of the emerging bioeconomy, or a need to find new revenue streams. These are the enterprises and individuals who should be part of the development of WWBR in South Africa.

These organisations can be grouped as either part of a large or niche industry, and as being present as a large or small entity. Niche industries may be more interested in higher value, lower volume products and are likely to be more agile in entering new markets and adapting their processes. Niche products may also benefit from industrial ecosystems through sharing distribution and logistics challenges through for example cooperatives. Larger concerns are often highly price competitive, and their main driver may be reducing costs. Large companies in either of these industry groupings may have more bureaucracy and innovation may struggle to find expression, while small companies may be more responsive in adapting and exploring processes to suit their needs. These are general trends and individual companies may not fit the generalisations. There may also be a number of smaller companies who are very active in the WWBR context but are difficult to identify as obtaining reliable information is problematic, not least because there are no standardised keywords or terms to use in searches.

9.1.3 Early-stage decision-making

The decision-making matrix in Figure 32 is a very early-stage attempt at facilitating choices when considering a WWBR using a specific waste stream. While it is suggested to have most, if not all units present for a resilient system, only one unit is likely to be optimised for bioproduct productivity. This heuristic process is intended to be a guideline only, to be further developed as more information becomes available, and for each specific scenario.

The question of desired product develops in parallel, and iteratively with the decision-making matrix, and can force a decision if a product can only be produced by, for example, an algal bioreactor.

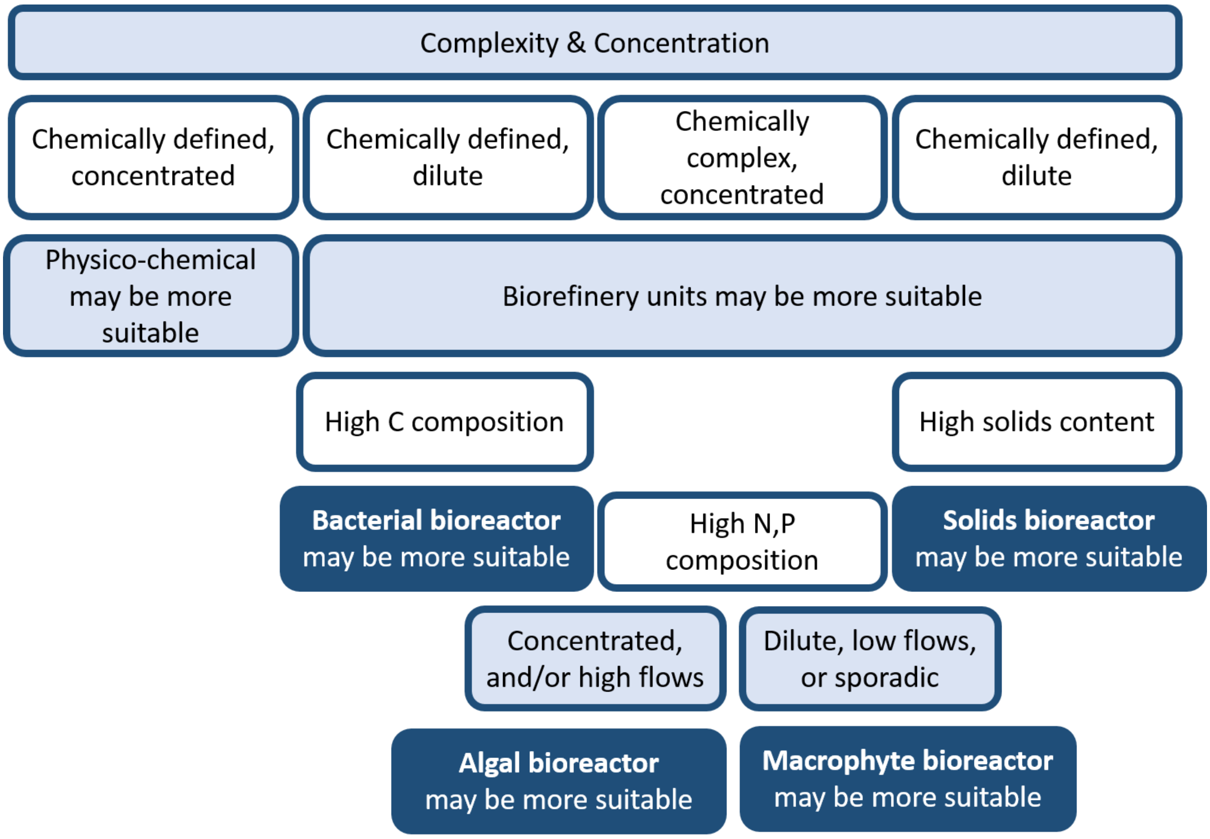


Figure 32: Decision-making matrix to guide selection of priority bioreactor

Table 116 is a qualitative comparison of the aspects at play if a stakeholder has a waste stream and needs to make a decision on a product group based on the capex and opex required. This could be the case where a utility is considering entering the WWBR space, but is coming from a culture of risk management and service delivery, or where an existing development has to be renovated.

Table 116: Comparison sheet for main priority reactor unit selection in WWBR

Category	Bacterial bioreactor	Algal bioreactor	Macrophyte bioreactor	Solids bioreactor
Maintenance	4	3	1	2
Opex	3	4	2	1
Operational effort	4	3	1	2
Operational skill required	3	4	1	2
Capex required per m^3 inflow	2	4	3	1
Space requirement per m^3 inflow	1	3	4	1

9.2 The Future of the WWBR

Going forward, effort is required in three broad areas: analysis, research and cooperation. Wastewater needs to be characterised in more detail and reported with a greater frequency. Industry players are encouraged to share wastewater samples, wastewater composition, general input and pilot-scale versions of their technologies with research institutions to facilitate integrated solutions that can scale.

Research needs to be directed towards testing existing technologies with appropriate detailed analysis, in pilot-scale integrated systems. Scientific research on promising products should to be adapted where needed and developed into engineering detail including, for example, yields in non-sterile systems with ecological selection, productivities and product recovery studies. Equally important, these companies and groups need to share their work to excite the public and gain the interest of niche industries who can help grow the circular economy. Because this is a complex, interrelating framework, a continuous serving of bite-sized and well-crafted publications over an extended time period, which make full use of social media, have a better engagement than singular scientific reports alone.

9.2.1 Better wastewater analysis and characterisation

One of the key hurdles recognised in the implementation of industrial ecology is knowledge brokering with respect to waste streams. Although information was obtained from numerous companies in the industrial, food and beverage, and mining and electricity generation sectors in South Africa in the study by Cloete, et al. (2010), most companies contacted did not perform analyses for the full spectrum of hazardous substances in the effluent.

Key findings from a pilot water disclosure project (CDP, 2009) included that most companies have information on their direct water usage, but most companies do not have data on water use or water issues in their supply chain. Also, while many companies have a water management plan, it is only for their own plants. Wastewater was not even explicitly mentioned, but most respondents identified water as an opportunity.

At time of writing there is still no system in place to regulate the level of detail required from metropolitan councils when obtaining information on effluent production, even for conventional wastewater treatment (especially regarding chemical composition). As a result, the data obtainable from metropolitan councils is inconsistent and comparisons are not always possible (Cloete, et al., 2010; WRC, 2015c). Some leading examples, such as the eThekwini Municipality, collect excellent data that can form a starting point for these investigations (Mabeer, 2015).

In order to investigate potential products from wastewater to contribute to a circular economy, a better understanding of the wastewater space and the inventory of potential raw materials is required. Focus on water as a “fit for purpose” key product is paramount. This requires better quantification of wastewater generation. Also, an understanding of the potential for reduced volumes and increased concentrations with increasingly water-wise processing is required to better predict future wastewater volumes, composition and resource recovery potential. The analysis and characterisation falls in a hierarchy of groupings, as illustrated in Table 117.

Table 117: Category of analysis groupings in order of priority for WWBR

Category	Parameters
Fundamental parameters	Total carbon Total nitrogen Total phosphorous COD Total solids content TSS
Factors affecting biological growth	pH Conductivity Heavy metals Toxins Chemically reactive inorganics Recalcitrant organics (e.g. phenols) FOG Detergents
Substrate Quality	Substrate characterisation (e.g. simple sugars, VFAs, cellulose) Presence of micronutrients, essential amino acids

From a qualitative perspective, process considerations can inform what is possible. For example, waters with a high oil content may be well suited to produce bacterial stress products such as surfactants. Pretreatment may improve the internal robustness of the process by improving the substrate quality, or to produce, for example, bioenergy. As the incoming substrates are analysed and characterised, the preferred 'major product' may change as all things are considered.

Water is a major product and may be the only one that exits the system as a whole, but this would still be a WWBR with the other products improving the internal economics. There should be a focus on higher value bioproducts as these may bring the greatest amount of economic benefit, but the rest of the products possible should not be ignored, as these can favourably affect the overall economic feasibility. Even if these products are only used to support the internal process, this still contributes to make the overall process more robust.

9.2.2 Pilot-scale integrated systems

Although the main purpose of pilot studies is to contribute technical knowledge of the integrated system, they also provide an opportunity to explore the methodology of determining wastewater data with the industries producing them, and establishing a standard for reporting wastewater that would be useful for WWBR. The pilot studies have as much of a social acceptance function as a technical one, and industry champions already active in the wastewater resource recovery sector should be encouraged to lead the charge. As such, the type of pilot systems to be studied depend on the champions' willingness to engage.

9.2.3 Cooperation across sectors

Desrochers (2001) opines that the most famous example of industrial ecology, Kulenborg Eco-Industrial Park in Denmark, was not a planned synergy, but rather one that evolved with time. The author concludes that developing an institutional framework that forces firms to internalise their externalities (by enforcing environmental regulation, for example), while leaving them the necessary freedom to develop new and profitable uses for by-products, should be given higher priority than the planning of localised industrial symbiosis. In South Africa, there seems to be a conflicting mix of enabling and obstructing factors in attempts at creating these frameworks. Some of these perceptions are listed in Table 118.

Table 118: Factors influencing the viability of WWBRs

Enabling factors	Obstructing factors
Existing thinking considering co-siting wastewater treatment works with organic waste management can improve logistics for industrial partnerships (e.g. Athlone solid waste management complex) (Coetzee, 2012).	Regulations may be inadequate (but not prohibitive); for example, classifying streams as waste legally limits their use/beneficiation.
Environmental impetus to improve water quality.	Poor quantification of wastewaters. A government-driven system is required to regulate the level of detail that metropolitan councils should go to in obtaining information on effluent production (especially regarding chemical composition).
Economic impetus from industry to reuse water and reduce cost of disposal.	In cases of adequate regulation, interpretation by authorities may still inhibit optimal use.
New biological reactor designs focusing on ecological niche enable novel routes to biological products; for example, Nereda system and work done at UCT on phosphate and nitrogen handling.	Current reactor design in existing plants may require retrofitting, current operator understanding may be inadequate.
Greater focus on holistic thinking and water-sensitive urban design provide potential for better integration between stakeholders.	Resistance to change in a bureaucratic environment.
Greater market push for biodegradable and more environmentally friendly products provide a market demand for (biological) products-from-waste streams.	A prevalent misunderstanding of the real market needs from the industries targeted for uptake of the products from wastewater.

Enabling factors	Obstructing factors
Environmental impetus to develop the industrial ecology and circular economy.	An unrealistic expectation of the real price obtainable from intermediate products by the producer (versus the advertised price obtainable for the finished products).
	An unrealistic expectation of the purity obtainable from products from wastewater – unrealistically expecting these to reach a similar price to highly pure product equivalent.
	Application/market reach of products from wastewater may be limited due to health or religious concerns. Food applications are out of reach. These are unlikely to change even as public perception and acceptance improves.
The large amounts of biomass currently not being adequately processed before export, combined with often limited existing infrastructure that would otherwise represent an opportunity cost, while considered typical of Africa, may represent a niche opportunity that suits small and medium enterprises well.	Limited understanding of how significant the impact of logistics is on realising product to market; for example, logistics is not the core business of the industry producing the wastewater and/or producing the product, thus a logistics partner needs to be found, with concomitant costs and challenges (aka having to manage yet another partner).
The typical decentralised nature of waste and highly site-specific requirements present a block for companies who need to operate at large scale with high efficiency, but presents an opportunity to smaller entrepreneurs.	

There is a perception among especially small-scale entrepreneurs that government policies on waste beneficiation are prohibitive. It does need to be acknowledged that government needs to manage the risk and health of the entire population, which includes its most vulnerable members. To improve policies (where needed), the interpretation of these policies and the perception of all stakeholders involved, government at all levels should be involved in the pilot integrated studies, voicing the risks and concerns from the design stages to manage these risks iteratively, and the onus on getting them involved is the responsibility of the people doing the study, be it academic or industrial researchers.

In this project, the City of Cape Town, including Mr Kevin Samson (Manager for the Wastewater, Water and Sanitation Department, Wastewater Branch), Mr Barry Coetzee (Manager for the Technical Strategic Support Utility Services Directorate and the Athlone WWTW) and Mr Michael Toll, were involved at various levels. They were responsive to emails and honest in their dialogue, which allowed key concerns to be incorporated, or at least, acknowledged early on in the project.

The importance of industrial bodies cannot be overstated, and these include those not directly related to WWBR. The Water Institute for South Africa (WISA) have periodic meetings, where the work could be presented, and more valuably, informally discussed with experts in industry. The African Utility Week allowed access to several industry groupings, and the discussions with the solid waste management industry stakeholders proved relevant. The WRC assigned a steering committee consisting of researchers and industry stakeholders from across the country, which is invaluable both for the members' direct contribution of their immense knowledge and experience, but also as a way to speedily transfer knowledge between the various research groupings represented, the research project in question and industry. These are only some examples of industry links.

For the WWBR to succeed, these networks need to be nurtured in formal and informal ways, small gains and challenges need to be continually shared. This goes further than creating another industry body, but relies on many, varied links in a healthy social ecosystem. In short, we need to play.

10 CONCLUSIONS AND RECOMMENDATIONS

Value from waste – recognising the tension between productivity and remediation

In addressing the growing needs of a world population, growing in both number and affluence, as well as the associated growth in environmental burden associated with waste assimilation, new thinking is required to address both waste treatment and resource productivity. Strongly emerging themes are those of valorization of waste and waste minimisation, namely, use the value of the resource to its full potential before classifying any part of it as waste. Application of this thinking is allowing early delivery examples to emerge globally, based on both industrial ecology and the application of second- and third-generation biorefineries (Section 2.2). Application of this thinking to wastewaters creates a tension in the approach. This tension centres around the relative prioritisation of delivery of clean water and the effective utilisation of the organic loading, nitrogen, phosphorous and heat within the wastewater, to name a few, with the associated maximisation of productivity towards the selected product(s).

Towards the WWBR

The development of the WWBR concept (Section 2.3) facilitates the use of multiple unit operations to allow simultaneous multi-criteria optimisation within the overall system. To develop this WWBR to reach its potential requires the integration of learnings from conventional wastewater treatment processes, bioprocess technology and environmental biotechnology towards implementing the principles of the circular economy, as well as process systems engineering for system optimisation.

The biorefinery concept has developed from its initial approach centred on woody biomass for largely energy-related products. The second-generation biorefinery concept extended the focus to multiple products while the third-generation biorefinery allows for variation in both feedstocks and major product(s) to meet varying needs for feedstock treatment and varying product demands (Section 2.2.3). The developing WWBR concept meets the third-generation biorefinery approach. The WWBR concept was launched in 2008 (Section 2.4.1). It has growing interest with six major research groups in Europe focused on its implementation (Section 2.4.3) and the first commercial applications are emerging in Europe (Section 2.4.2). Global application has yet to be seen. In this report, we focus on refining the WWBR concept, identifying its guiding principles and constraints, the challenges of its implementation and its applicability to South Africa.

Towards the wastewater biorefinery in South Africa

In South Africa, the WRC has championed substantial research into wastewater treatment (Section 2.5). While much of it is focused on removing pollutants alone or on cleaner production, a number of example projects do provide research on which to build the WWBR concept (Section 2.5.6). Specifically, in systems implemented for the combined treatment of wastewaters towards clean water with simultaneous value addition in South Africa, only biogas projects have been implemented for value generation (Section 2.7), with examples of integrated water treatment and biogas generation towards heat, electricity or steam including systems using both municipal wastewater and industrial wastewaters as feedstock. The former include the City of Johannesburg Metropolitan Municipality (2.7.3) while the latter extends from large-scale anaerobic digestion of petrochemical wastewaters at Sasol sites and PetroSA, application on the larger breweries within the SABMiller for steam generation, treatment of abattoir effluent through to small-scale anaerobic digesters distributed across a range of wastewaters (2.7.2). It is suggested that the use of anaerobic digestion for water treatment with biogas generation for conversion to electricity is under-reported in South Africa and is driven by increasing electricity prices and insecurity of electricity supply. Increasingly, research projects are seeking to extend the product spectrum from wastewater treatment beyond clean water and energy, with pilot studies being implemented on the production of algae from wastewater, production of elemental sulphur from acid mine drainage, and the implementation of wetlands.

In South Africa, there are competing tensions on the implementation of WWBR for simultaneous water treatment and value creation. On the one hand, a lack of skilled personnel in the wastewater treatment arena demands the implementation of simple and robust technologies. On the other hand, the simultaneous treatment of waste with value creation can generate the resources required to sustain the treatment facilities (Section 3.1.1). Further, developing an integrated approach with the combined potential for wealth creation, upskilling and job creation in a region or community can motivate for its efficient operation by that region or community, prioritising it over the less tangible water treatment.

The current low compliance in terms of wastewater treatment in South Africa makes it a target for investment (Section 3.1.2), providing opportunity for implementation of new approaches. The potential for value generation may assist to motivate the investment. Furthermore, it may drive the efficient operation of the facility to maximise value (Section 3.1.1). An additional current driver in South Africa is the growing water scarcity, necessitating new approaches to increasing available water and its governance. Sustainable water treatment services thus become a necessity to ensure water availability. This may benefit from new financing models, including PPPs and other opportunities to bridge the current funding gap (Section 3.1.3).

The WWBR strives towards zero waste by valorizing elements of the wastewater stream through maximising nutrient reuse and recycling by generating biobased products and energy while ensuring the compliance of the resultant water stream (Section 2.3). To further evaluate the potential for WWBR in South Africa, a review of the nature of the wastewater feedstock in South Africa is presented (Section 4.1). This is followed by a rudimentary inventory of wastewater resources across a number of key sectors in South Africa (Sections 4.2 and 4.3). A discussion on products of interest is presented (Chapter 5) with two polymeric commodity bioproducts discussed in more detail (Section 5.4). Together, these position the applicability of the WWBR. This has been followed by an evaluation of key criteria of the WWBR, requirements of the WWBR reactor systems (Chapter 6) and the generation and analysis of the integrated WWBR flowsheet (Section 7.1).

South Africa's wastewater feedstocks

A review of South Africa's wastewaters demonstrated a considerable resource value. To utilise this, an inventory of the available resources is required. A number of attempts at this data collection have been made; however, it remains incomplete and much of it is dated. The data on waste streams tends to be reluctantly communicated by industry. A slow response to carbon disclosures has been evident through the CDP of 2015 and illustrates the major challenge around information brokering that is so essential for effective implementation of industrial ecology of which WWBRs are a subset. Further, the level of data collection presented in the reports is fragmented and incomplete.

The importance of characterising the available waste streams in terms of their volume, concentration, overall inventory and complexity is essential (Section 3.2.2). The relative availability of carbon, nitrogen and phosphorus, as well as stream complexity will drive the applicable uses of each stream. Further to this, stream variability in composition and volume, as well as seasonality is key in informing application for each stream. Through an initial data collection exercise, significant carbon availability has been estimated across the following industries (million tonne per annum): municipal wastewater 4.6 (Section 4.2), dairy industry 3.9 (Section 4.3.3), petroleum industry 1.8 (Section 4.3.2), pulp and paper industry 1.0 (Section 4.3.1) and edible oil 0.5 (Section 0) with high associated nitrogen availability in the following streams (in descending order): municipal wastewaters, pulp and paper, dairy, abattoir, and beverage industry wastewaters. This estimation is given in Chapter 4 with detail in Appendix C.

A common reporting framework is not in place – at the level of metropolitan councils or any other entity – resulting in incomplete data reported in inconsistent units etc. Discrete examples of state-of-the-art data collection such as that conducted by eThekwini Municipality (Appendix C.3) demonstrate the value of such data. Development of such a reporting framework will be valuable as will be populating it with up-to-date data with associated geographical details. This will both allow categorisation of wastes in terms of their complexity, concentration and volume and their potential for use within a location. In the collection of these data, cognisance of the dual approach i.e. both water treatment and product creation, is required. It is suggested that a careful definition of required dataset be drawn up and the form of data be specified. For example, for the purposes of WWBR, determination of the available carbon in terms of elemental carbon is more valuable than collecting the information as COD (Sections 4.1.2 and 7.3.3). It is anticipated that much of this required up-to-date data will come available through the NatSurv reports currently being compiled (Section 4.1.1).

Potential products from the WWBR

With such an inventory available, there is potential to match products and appropriate technologies to the treatment of raw materials. The product spectrum considered should ideally be informed by the market pull and can be informed by the DST's current studies on biobased products for South Africa's bioeconomy.

A number of factors inform product selection (Section 3.3). In the first instance, a demand for the product(s) selected is essential. It is most preferable for the product to find application within the sector from which the waste is generated, linking the market demand to the waste produced. Where this is not possible, a market within the geographic region is preferred. Secondly, where large-volume wastewaters are treated, the production of commodity products able to fully utilise the nutrient resource, are favoured owing to the competing requirements for products of value and clean water. Further, it is not desirable to target high purity products-from-waste feedstocks, further supporting commodity products. Finally, separation of the product from the often dilute wastewater stream is required. For this, products reporting to a phase other than the aqueous phase is preferred.

WWBRs incorporate multiple unit operations to ensure removal of all nutrients and the combined optimisation of multiple products not possible from a single unit operation. Hence, products must be selected to address removal of each set of nutrients. While the juxtaposition of these products and their integration through the unit operations of the WWBR has been considered in later chapters, an analysis of a number of potential products to be produced from the WWBR is presented in Chapter 5, with initial focus on the carbon-rich product. This product spectrum aligns well with those highlighted with potential for the biobased economy, both in South Africa and abroad, including platform chemicals, biobased plastics and polymers, biomaterials, biosurfactants, biolubricants, biosolvents, enzymes, organic acids and amino acids, animal and aqua-feeds, soil improvers and bioenergy products. Biopolymers, such as the bioplastics PLA, PHA (Section 5.4.1) and PGA (Section 5.4.2) used as a flocculant for metal removal and for water retention, have been highlighted as products of interest.

Integrating bioreactor design and the WWBR flowsheet

Through focus on the first reactor in the WWBR process flowsheet, we have explored key requirements of the bioreactor design in the WWBR (Chapter 6). The nature of the feedstock as typically dilute and potentially complex places a requirement on the bioreactor for decoupling of the biomass retention and HRTs (Section 6.1). By retaining the biomass within the reactor (increasingly important with decreasing feedstock concentration), a critical biocatalyst concentration can be achieved to allow rapid passage of the feedstock through the reactor with efficient conversion. This is augmented where the biological phase has an ecological niche. Together these remove the need for sterilisation; owing to the large flows, it is essential that no sterilisation is required to attain a robust process. Decoupling of biomass and HRTs allows continuous, or semi-continuous, operation to be ensured as wastewaters cannot be stored. As discussed above, the bioreactor system must be designed for product recovery (Section 6.1.3). Most typically, it is desirable to achieve this by partitioning the product into a phase other than the aqueous phase, thus eliminating the need to separate it from the large-volume aqueous phase. Thus, the ease of product recovery should be considered in an integrated manner with bioreactor design.

The bioreactor selection for the WWBR is proposed to meet the above requirement while being drawn from those reactors already used in wastewater treatment to ensure familiarity for the operating staff and potential to retrofit the reactors (Section 6.2). The activated sludge, BNR, PBR, FBBR, TBR, MBBR and AGSR and RBC bioreactors were considered. These were assessed against the above criteria, leading to the RBC, AGSR and MBBR being shortlisted as the most promising in terms of potential for biomass retention and product removal, listed in order of ascending preference (Section 6.4). Associated with this study, experimental investigation of the MBBR (Appendix E) to produce the product PGA (Appendix D) has been initiated.

As an illustration of the WWBR, a flowsheet (Section 7.1.1) has been compiled through this study comprising: 1) solid-liquid separation; 2) a bioreactor to reduce the organic load with simultaneous product of a polymer product, typically using a bacterial (or yeast or fungal) system (Section 7.4); 3) an algal bioreactor system for removing trace organics, nitrogen and phosphorous (Section 7.5.1); 4) a macrophyte bioreactor for polishing the water with respect to nitrogen and phosphorous (Section 7.5.2); and 5) a solids bioreactor (typically fungal) utilising SSF to handle the sludge (7.5.3).

There is potential to add and subtract units, e.g. add an anaerobic digester to produce electricity, heat or both. Potential also exists for multiple units in each of these categories. From this generic flowsheet, the product spectrum includes the microbial bioproducts such as the biopolymer, algal oil, algal bioproduct, macrophyte fibre and biomass, compost, sludge products, bioenergy and clean water. A simplified but integrated material balance model has been established using this generic flowsheet (Chapter 7). It has been populated with typical performance data for these biological systems (Section 8.1). The generic flowsheet model forms the key tool for the exploring of WWBR scenarios to investigate the potential of this approach.

Exploring the WWBR flowsheet through selected example processes

The generic flowsheet and material balance model assembled in this study provide a useful tool to analyse the performance potential of the WWBR. Through its demonstration in terms of the bacterial bioreactor for the production of the biodegradable plastic PHA from confectionery wastewater (Section 8.2), its usefulness and potential for refinement has been demonstrated. Further flow visualisation using the Sankey diagrams is demonstrated. The use of elemental compositions of the wastewater in terms of carbon, nitrogen and phosphorous is preferred over the electron balance approach of COD, owing to the need for substantial additional information for the use of the latter in the material balance. The need to simultaneously optimise the compliance of the outgoing water stream and the productivities of desired products drives the motivation for the integration of multiple unit operations.

An integrated WWBR approach is demonstrated to treat municipal wastewater with the generation of the polymer PGA, algal products, macrophyte products and fungal products (Section 8.3). Low productivity of the macrophyte reactor compared with the algal reactor system suggests the need for scenario analysis around their relative contribution. Further potential exists for refinement of effluent compliance, with scenario analysis proposed to address this. In the final demonstration of the material balance model, the performance of the WWBR is compared regarding use of different wastewater streams with differing nutrient provision (Section 8.4). The municipal wastewater was compared to a nitrogen-rich poultry abattoir effluent and to pulp and paper wastewater. The proportions of products of interest are altered to meet the differing elemental loads and concentrations within the wastewaters, thus demonstrating the flexibility of the WWBR. The availability of nitrogen in the wastewater favoured the bacterial and algal products while in the presence of excess carbon, more carbon reported to the lower value products. There is substantial potential to refine this partitioning through an improved understanding of the system. This can be facilitated through scenario analysis using the material balance tool.

Revisiting and refining the WWBR concept

Through characterisation of a range of wastewaters in South Africa, the significance of South African wastewaters as a resource for biobased products is evident, with in excess of 12 750 tonne carbon, 325 tonnes nitrogen and 77 tonne phosphorous available per day from the wastewaters reviewed. While a key focus of the process industries and of society is to reduce the waste streams formed, both in terms of water and organic components of the waste, the ongoing prominence of waste streams is clear. This accentuates the need for the closure of water and nutrient cycles, both to maximise resource productivity and to address water scarcity in nations such as South Africa. Through this, the importance and potential of WWBRs is highlighted.

In order to realise the potential benefit of these waste streams in terms of both water and bioproducts, the challenge presented by these wastewaters must be acknowledged. This includes the complexity and variability of many waste streams. Their effective use requires rigorous analysis and characterisation of the wastewater streams, as well as the effective communication of this information. Furthermore, information on the magnitude of the resource and its complexity on a geographic basis is necessary for the application of the WWBR concept.

Based on the resources available, meta-research on products of interest, their market demand and suitability and their production systems through microbial, algal or plant systems is required. In this analysis, the relevant bioreactor design for application in the WWBR, addressing the provision of a niche environment for desired biocatalysts to avoid sterilisation is required. Further, bioreactor design should address the decoupling of hydraulic and biomass residence times as well as design for product recovery, preferably into a different phase. The success of this approach stands to benefit from the integration of traditional bioprocess engineering approaches and environmental bioprocess approaches used in remediation systems. The application of these bioreactors and associated product systems require demonstration at both laboratory and pilot scale, as unit operations and as integrated systems.

Pilot-scale demonstration of integrated systems is required for the validation from a technical perspective both of the unit operations and of the integration of the complex processes. Through this data, the meeting of the dual aims of achieving compliance of water for reuse and closing nutrient cycles to enhance resource productivity can be considered. Further, the social value of the system requires demonstration, contributing to the acceptance and desirability of the WWBR approach. Such holistic communication leads to cooperation and incentivisation of investment, as well as social acceptability.

Recommendations

The potential of WWBRs in South Africa is clearly demonstrated through this study. This is seen through the availability of a substantial feedstock with potential for bioconversion, the significant capacity for value addition, the opportunity for focus on innovation in water treatment and the potential for improved performance in water treatment and standards compliance through the incentivisation through value addition inherent to the WWBR. In addition to drawing attention to this potential, it is recognised that considerable development of the concept is required to facilitate its application. In this section, a number of areas for further work are highlighted with accompanying recommendations.

The review of WWBRs worldwide has illustrated that this concept is nascent globally and that South Africa is well positioned to contribute substantially. South Africa has a well-developed research community on water treatment and it is recommended that a number of aspects of completed research can be harnessed towards the WWBR by the continued engaging of our research capability and the development of consortia. Further, owing to the investment currently required in our wastewater treatment industry even in terms of traditional treatment options, it is timely to integrate treatment with valorization with the aim that simultaneous treatment and value creation may incentivise compliance. The simultaneous quality water treatment and production of products of value may thrust South Africa and its infrastructure providers into the forward-thinking arena of the circular economy.

The following specific recommendations are made:

1. It is proposed that a framework for data collection be compiled and an improved inventory across the industry be gathered, as the knowledge base on South African wastewaters was incomplete at the time of compiling this report. In this inventory, information on volume, concentration and complexity of the wastewater should be reported. Further, for material balancing, it is proposed that the basis of elemental composition is used and that geographic information is incorporated, in addition to industry averages.

2. It is suggested that a rigorous set of preferred products be identified that are robust and suitable for production from specified waste resources, through the integration of current research on the preferred bioproducts for South Africa's biobased economy and the development of the inventories proposed above. This selection should be informed by market research and a clear understanding of the customer of the product. A distinct advantage of developing products for use in the same industry from whence the waste came is recognised, thus securing product market.

3. It is suggested that targeted research on the relevant product spectrum from the solids and macrophyte bioreactor systems be conducted, with a specific focus on indigenous species and consortia. Limited research has been conducted on these unit operations, and they form a key requirement for water compliance.

4. In this study, focus has been placed on the bacterial bioreactor design for the WWBR. Testing is required in the laboratory and on the plant for implementation of the concepts proposed for these bacterial bioreactors.

5. The bioreactor design studies conducted as part of this project should be extended to the other bioreactor units: algal bioreactors, macrophyte bioreactors, sludge digesters and SSF bioreactors for sludge utilisation.

6. The flowsheet approach and material balance model provide a good framework for analysis of varied scenarios for value creation from waste using the WWBR. Analysis of the current scenarios suggests value in process refinement to enable a larger partitioning of the major resources to the products of most value. This refinement should be undertaken and the material balancing tool applied to varied scenarios. By refining the material balancing tool and the process flowsheets proposed, progress towards this goal will be achieved. Following the refinement of the flowsheet and model, their further use in scenario analysis is proposed to identify the most promising approaches for further study.

7. It is proposed that promising wastewater streams for resource recovery be identified using the rudimentary inventory presented in Chapter 4. These are recommended to form the subject of case studies around which to further develop the thinking behind, technology supporting and implementation of the WWBR. This has been initiated in the sugar, abattoir, paper and pulp, beverage and domestic wastewater sectors at a preliminary level through this project and should be extended. It is through detailed case study research and scenario analysis that an in-depth understanding of controlling factors will be derived.

8. Following implementation of recommendations (6) and (7), it is proposed that environmental analysis through e.g. LCA and techno-economic analysis be carried out for specific and promising scenarios.

9. It is suggested that the impact of WWBRs be interrogated in terms of their potential for social benefit as well as acceptability. This action will need to be well integrated with the role of communication in the understanding of social benefit and buy-in from the community. It is proposed that this be explored through a pilot study.

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A WRC WASTEWATER REPORTS

From the 2410 WRC reports provided in the database and discussed in Section 2.5 232 reports were selected (based on title and a brief overview of executive summary, in most cases) for potential relevance to wastewater biorefineries. These 232 reports, spanning 31 years of research from 1984 to 2014, are listed here. The reports are sorted on category first, then date of publication. An electronic copy of the table can be found at https://www.dropbox.com/s/m2padaunrdsi1cc/WRC_reports_12mar15.xls?dl=0

Table: A-1: Analysis of WRC wastewater report references

Category	Ref No	Authors & Title of Report	Year of publication	Value of research in context of wastewater biorefineries	Shortcoming of research in context of wastewater biorefineries / more work required
A	1	2085/1/14: Mitchell SA ,de Wit MP, Blignaut JN, Crookes D. Wastewater treatment plants: the financing mechanisms associated with achieving green drop rating	2014	Financing mechanisms of wastewater treatment plants	Improve the performance of WWTWs through providing an incentive to the works in the form of a scoring system. Limited applicability to WWBR, except as an operational incentive mechanism.
A	2	TT 588/13: Armitage N, Fisher-Jeffes L, Carden K, Winter K, Naidoo V, Spiegel A, Mauck B, Coulson D. Water Sensitive Urban Design (WSUD) for South Africa: Framework and guidelines	2014	Biological and chemical treatment of associated contaminants, drainage and the management of industrial effluents. Water-Energy-Food Nexus. Wastewater re-use and minimisation.	Big picture of WWBR and beyond.
A	3	1826/1/13: Armitage NP, Vice M, Fisher-Jeffes L, Winter K, Spiegel A, Dunstan J. Alternative Technology for Stormwater Management	2013	Consider storm water as part of the urban water cycle	Integrated WWBR in urban environments. Using the sustainable drainage as (macrophyte) reactors.
A	4	1941/1/13: Naidoo N, Longondjo C, Vrdoljak M. Investigating operations and indigenous knowledge of water use and waste management, and establishing ways to integrate them into water services management	2013	This research was aimed at introducing communities, municipalities, practitioners, etc across South Africa to alternative ways of managing water and to allow indigenous knowledge to inform future policies. The report finds in line with general consensus that indigenous practices are environmental sustainable.	Adapting Indigenous water knowledge (IWWM) practice to suit current conditions requires that planners understand the full local environmental implication of the technology before it can be implemented. It was concluded that IWWM could assisting in addressing various challenges currently facing the water sector, and in the WWBR context how the system could fit together.

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A	5	2087/1/P/1: SG Hosking SG, Jacoby KT, Trends in the Insight into the Growing South African Municipal Water Service Delivery Problem	2013	The study investigates the setting of water tariffs that cover costs and satisfy demand. An analysis of efficiency in the mix of water service output is one that aims to match demand to the service produced.	Evidence of failures in water service delivery are mounting, due to lack of political will, funding, low skill capacity. Study contextualizes and analyses this situation. Applicable to WWBR in that WWBRs and WWTWs would be run by a similar system, and so curreny weaknesses would likely carry over to WWBRs.
A	6	TT 518/12: Schulze RE, A 2011 perspective on climate change and the South African Water Sector	2012		The effect of climate change on hydrological responses. Predictive scenarios, indicating risk levels, for the biophysical changes associated with projected climatic change for climatically divergent catchments in South Africa were then developed.
A	7	1921/1/12: Malan HL, Day JA, Water Quality and Wetlands: Defining Ecological Categories and Links with Land-use	2012		Possible application to WWBR macrophyte bioreactor.
A	8	1840/1/11: Jeleni A, van Rooyen PG, Behrmann D, Nyland G, Hatting L, Sussens H, Integrating Water Resources And Water Services Management Tools	2011	An approach for integrating Water Resources and Water Services management tools, and to develop a Generic Integrated Framework, which can incorporate relevant and appropriate water management tools that are used both in water resources and water services	Water resource tools could be used in WWBRs, in a similar way to their current use.
A	9	1839/1/10: Braid S, Görgens A, (editors). Towards the development of IWRM implementation indicators in South Africa	2010	The meeting with the Municipality raised some very pertinent points about integration vs. co-ordination, and notification vs. engagement between the government institutions, both across sectors and across spheres of government, highlighting the 'edge' effects in the institutional structure. The examples provided by the Municipality (although one-sided), suggest that IWRM is understood, but that the hurdle lies with the administration and implementation.	Only partially relevant as a way to establish the understanding of WWBR by different stakeholders.
A	10	TT 395/09: Oosthuizen NL, Bell J, Managing your wastes to achieve legal compliance: An industry guide (and TT 396/09 ,TT 397/09 TT, 398/09)	2009	Managing waste to achieve legal compliance	Legal compliance of wastes management for industry, that WWBR should also comply with.
A	11	1449/1/07: Nogni EV, Musvoto, Ramphao MC, Characterisation of Wastewater from Low Income High Density residential	2007	Characterisation of Wastewater from Low Income High Density residential areas	Need more work to fully characterize WW for bioprocess applications. WW found to be within assumptions for municipal WW.
A	12	TT 310/07: Duncker LC, Matsebe GN, Nancy, The social/cultural acceptability of using human excreta (Faeces and Urine) for	2007	The social/cultural acceptability of using human excreta (Faeces and Urine) for food production in rural settlements in South Africa	General overview of human consideration of waste – social aspect. Further work required on where this acceptance boundary lies, with e.g. bulk chemicals

Category	Ref No	Authors & Title of Report	Year of publication	Value of research in context of wastewater biorefineries	Shortcoming of research in context of wastewater biorefineries / more work required
		food production in rural settlements in South Africa			
A	13	1479/1/06: Murphy OK, A scoping study to evaluate the fitness-for-use of greywater in urban and peri-urban agriculture	2006	An investigation of re-use of greywater – including volume assessment, composition and characteristics.	More work required to contextualize (modular) wastewater biorefinery units in the urban and peri-urban context – starting with a feasibility study
A	14	1344/1/06: Banister S, Zhao B, Coetser SE, Pulles W, The assessment and classification of inorganic manganese containing wastes.	2006	Including biological treatment of Mn	Not only for Mn recovery, but may be a good supplement for Mn-requiring biocatalysts (PGA producer)
A	15	1548/1/06: Brice J, Sevitz J, Cornelius J, Guidance for the classification, rating and disposal of common hazardous waste streams	2006	Hazardous solid waste (chemcial, electronics, medical)	Limited application to WWBR, may apply when these streams are used in WWBR context, when knowledge of their management becomes necessary.
A	16	KV 166/05: Muller JR, Approaches to abattoir effluent treatment.	2005	This report details the full scale use of a modified Sequential Batch Reactor process for the pre-treatment of abattoir effluent and for protein production. A costing and pay-back analysis is also presented.	The technology presented could be very useful in a WWBR dealing with abattoir wastewater. The report demonstrates the full scale operation of an economically sound process.
A	17	1430/1/05: Schulze RE, Climate change and water resources in Southern Africa	2005	Management of scarce water resources with climate change implications	Context
A	18	1467/2/05: Cullis J, Rossouw JN, Gorgens AHM, First order estimate of the contribution of agriculture to non-point source pollution in three SA catchments: Salinity, Nitrogen and Phosphorus.	2005	Agriculture, in its broadest sense, appeared to have a major impact on salinity loads, particularly in areas with a high degree of irrigation and natural saline geology. It was also found that the net agriculture non-point source (ANPS) load was greatest during the wet season and in some cases, such as in the Breede, there appeared to be a "first flush" impact at the start of the wet season.	Contextual information, argument for more integrated nutrient cycles.
A	19	KV 151/04: Murray K, du Preez M, Lebone M; Pearson IA, Understanding the sustainable management of small water treatment plants in rural communities: a systems thinking study	2004	Besides technical issues, a number of social and institutional issues were noted as having received inadequate attention in the past. It was believed that this was often responsible for lack of sustainability. This report investigates a "systems thinking" approach to a better understanding of these issues and their inter-relationships in this challenging context. The objectives of this project were as follows: To test the use of a systems approach for analysing the issues affecting sustainable management of small water treatment plants in	Methodology of systems thinking. WWBR needs to give attention to four potential barriers to information flow: Community articulation of needs and supplier receptiveness to those needs, and, Supplier articulation of potential solutions and community receptiveness to those solutions.

Category	Ref No	Authors & Title of Report	Year of publication	Value of research in context of wastewater biorefineries	Shortcoming of research in context of wastewater biorefineries / more work required
				rural communities. To test the use of a systems approach for developing generic process guidelines that will complement existing technical guidelines and facilitate sustainable management in future.	
A	20	456/1/04: Barclay S; Buckley CA , The regional treatment of textile and industrial effluents	2004	Regional relevance	
A	21	1033/1/04: Pillay VL, Caustic management and reuse in the beverage bottling industry	2004	The report details the use of membrane separations in order to recycle used caustic solution.	Limited direct applicability of caustic recycling to WWBRs, but membrane separations technology will be important in WWBRs and so the methods used to evaluate membranes in this study could be adapted for use in WWBRs.
A	22	1184/1/04: Freese SF, Trollip DL, Nozaic DJ, Manual for testing of water and wastewater treatment chemicals	2004	Manual of standard procedures for wastewater authorities to use for evaluation of the chemicals used in water and wastewater treatment.	The methodologies set out in this manual will be important to use in WWBR reagent testing.
A	23	1191/1/03: Cloete TE, Thantsha M, Microbial characterization of activated sludge mixed liquor suspended solids	2003	An important design parameter in activated slude WW treatment is active biomass. The objective of this investigation was to use ATP as a method to determine the active biomass fraction in activated sludge, from commercial plants.	The methodology shown in this report could be very useful in WWBRs, however, further work is required to demonstrate that the method works accurately in other systems.
A	24	820/1/00: Naidoo V, Buckley CA, Municipal wastewater characterization: Application of denitrification batch tests	2000	Municipal wastewater characterization. Wastewater is a complex substrate consisting of compounds of differing biodegradability. The organic matter is discussed in terms of chemical oxygen demand (COD). Biokinetically, these compounds have been divided into readily biodegradable (RBCOD), slowly biodegradable (SBCOD) and unbiodegradable substrate groups. Compounds with intermediate biodegradability i.e. compounds which fall between the RBCOD and SBCOD groups, have been termed readily hydrolyzable organic substrates (RHCOD). The readily biodegradable and readily hydrolyzable COD fractions of wastewater can be determined by respirometric tests such as the oxygen utilization rate (OUR) and nitrate-N utilization rate (NUR) tests.	Limited application to WWBR, gives somewhat of an overview of municipal wastewater composition. Also perhaps more up to date reports exist.
A	25	201/1/99: Buckley CA, Research into the treatment of inorganic brines and concentrates	1999		
A	26	241/1/98: Pillay VL, Research on the filtration of compressible cakes	1998	Filtration is widely employed in the water industry, for the clarification of suspensions, the concentration of suspensions and the dewatering of sludges. In most instances, the cakes formed are compressible, i.e. it undergoes changes to its structure and properties during the	Applicable to WWBRs for product recovery and unit operation.

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				filtration process. This can significantly affect the performance of the filter, as well as introduce seemingly spurious system behaviours. The objectives of this project are as follows : (i) to investigate the mechanisms responsible for compressible cake behaviour, (ii) to investigate the effects that compressible cakes have on filtration systems, (iii) to investigate methods to characterise cake compressibility, (iii) to identify and develop models and equations to predict filtration performance for compressible cake systems.	
A	27	708/1/98: Du Pisani JE,The operation and maintenance of settled sewerage (SS) systems in South Africa	1998	the operation and maintenance requirements of settled sewerage systems in South Africa.	Design requirements of equipment. Social understanding and acceptance
A	28	239/1/98: Cowan JAC, The transfer of waste-water management technology to the meat processing industry	1998	This report details the deployment of a pilot plant equipped with ultrafiltration and reverse osmosis to be used by a major inndustrial abattoir, to test the system's capabilities at no significant financial or technical risk to the industrial partner.	The technology implemented here at pilot scale could be of use in a WWBR, for the concentration of high COD wastewaters. However, applicability in a number of industrial wastewaters needs to be demonstrated.
A	29	161/1/94: Gubb & Inggs Ltd, University of Natal, Research into the treatment of wool scouring effluents	1994	the liquid wastes emanating from the commercial scouring of such wool have long been regarded as highly polluting and difficult to treat. Includes a techno-economic feasibilty study	further work be carried out on the use of dynamic membranes for the treatment of wool scouring effluent,
A	30	TT 45/90: SRK, A guide to water and waste-water management in the red meat abattoir	1990		
A	31	TT 46/90: SRK, A guide to water and waste-water management in the poultry abattoir industry	1990	Poultry abattoirs are graded according to their maximum permissible throughput into five grades namely AP (> 10 000 birds/day) to EP (maximum 50 birds/day). AP-grade poultry abattoirs constitute only a small fraction (13%) by number of the total number (149) of abattoirs in the RSA (1990 values) but carry out the bulk of the production, namely more than 93% of the total number of broilers processed annually. Opportunities for reclaiming and recycling water are identified, and the potential for water saving in the Industry is indicated to be around 1 600 Mi/a, which is equivalent to 29% of current consumption by the Industry. In large, modern, AP-grade abattoirs, the specific effluent volume (SEV) is typically around 15 i/bird and the specific pollutant load (SPL) in terms of chemical oxygen demand (COD) is typically around 27 g COD/bird. The	Effective usage of water in the poultry industry to comply to meat hygiene regulations as well as devising treatment methods to reduce pollutant load in the wastewater. Can this wastewater be used in a WWBR? How out of date is this information?

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				principal contributors to SEV and SPL are the operations carried out for evisceration (33% of SEV, 48% of COD SPL), washdown (22% of SEV, 35% of COD SPL) and scalding (17% of SEV, 11%of COD SPL). Nationally, pollutant loads estimated for the Industry are an effluent volume of 4 900 Mi/a and mass pollutant discharges of 10 255 t/a of COD, 2 450 t/a of SS and 4 970 t/a of TDS.	
A	32	TT 48/90: University of Natal, A guide for the planning waste-water treatment plants in the textile industry Part 3: Closed-loop treatment/recycle options for textile scouring bleaching and mercerising effluents	1990	The project focussed on textile wastewaters; characterising effluents, developed possible treatment options for each effluent, assessed each system at laboratory and pilot-scale and developed basic design criteria for the implementation and installation of selected systems.	The methods developed in this report could be applied to WWBRs which treat WWs from textile plants.
A	33	75/1/90: Beekman HG, Klopper DN, Fawcett KS, Construction and operation of the Cape Flats water reclamation plant and the surveillance of the reclaimed water quality	1990	The project developed a large scall process to produce potable water from the Cape Flats wastewater treatment facility, and integrate this water with current water delivery.	The technology deployed in this report is one which could be utilised by WWBRs in their final production of potable water.
A	34	106/3/87: University of Natal, Investigations into water management and effluent treatment in the fermentation industry	1987	An investigation into the water management and effluent treatment in the processing of (i) Pulp and Paper, (ii) Metals, (iii) Fermentation Products and (iv) Pharmaceutical products	Survey on wastewater management and effluent treatment/control in the fermentation industry
A (SOCIAL)	35	TT 564/13: Wall K, Ive O, Social Franchising Partnerships for Operation and Maintenance of Water Services: Lessons and Experiences from an Eastern Cape Pilot	2013	An investigation of the business model that could occur in the sanitation sector	The project is aimed at a more social responsiveness and community level. It would be interesting to see if this can be extended to a bioproduction facility context.
A AGRIC	36	1497/1/07: Holl MA, Gush MB, Hallowes J, Versveld DB, Jatropha curcas in South Africa: An Assessment of its Water Use and Bio-Physical Potential.	2007	The water use of Jatropha curcas grown for biodiesel production	Limited applicability to WWBRs, although the wastewater byproducts of biodiesel production would be of interest.
A ANAL	37	1283/1/04: Snyman HG, Herselman JE, Kasselman G, A metal content survey of South	2004	A metal content survey of South African sewage sludge	More work required to determine the impact of these metals on the bioprocesses to be used in a wastewater biorefinery context

Category	Ref No	Authors & Title of Report	Year of publication	Value of research in context of wastewater biorefineries	Shortcoming of research in context of wastewater biorefineries / more work required
		African sewage sludge and an evaluation of analytical methods for their determination in sludge			
A ANALYSIS	38	1339/1/07 Jaganyi D, Methodology and survey of organic pollutants in South African sewage sludges: Volume 1	2007	An organic pollutant content survey of South African sewage sludge	More work required to adapt these to monitor and analyse the components in the bioprocesses
A ANALYSIS	39	1286/1/07: Pillay B, Dechlan, Development and application of prokaryotic biosensor systems for the evaluation of toxicity of environmental water samples.	2007		Potential way to evaluate incoming wastewater to prevent system failure
A ANALYSIS	40	1459/1/07: Wolfaardt JF, Grant R-M, Kock MM, Characterisation of planktonic microbial populations in paper-mill water	2007	Integrated water management plans for paper mills include strategies to reduce water consumption by closure of water circuits to reuse water. Closure, however, directly and indirectly results in an increase in populations of microorganisms. Comprehensive characterisation and identification of microbial populations could result in improved control and will extend the limits for mill closure. Microbiological data could also aid in the prevention of biofilm formation and minimise corrosion and furthermore be useful to minimise health risks and improve efficiency of water treatment processes.	It is recommended that the database and key software be distributed as widely as possible and not only within the paper industry, but also to other industries where bacterial control and identification play a role. Environmental parameters in water systems influence microbial numbers and parameters such as temperature and oxidation-reduction potential should be used to predict microbial levels. These data will be invaluable for integrated water management and especially when water systems are to be closed.
A ANALYSIS	41	TT 180/05: CSIR Water and wastewater management in the oil refining and re-refining industry: NATSURV 15	2005	Determine the volume of water intake and discharge in oil refineries and re-refining industry	A breakdown of water usage and the pollutant loads were presented and recommendations were made for water and wastewater management
A ANALYSIS	42	TT 240/05: Van Zyl HD, Premlall K, Water and waste-water management in the power generating industry (NATSURV 16)	2005	Investigation of water consumed and how to minimise it in power generating industries. Twenty nine power stations situated countrywide collectively produces approximately 192 000 GW of electricity per annum. To achieve this, approximately 245 000 Ml of water is consumed. The effluent produced is much less than this, as up to 80% of this water is lost through evaporation in cooling towers. The average raw water intake / unit sent out (RWI) is dependent upon the type of power generating process, whether open or closed loop cycles are used, the type of cooling and ashing processes utilized, as well as the quality of raw water. The average RWI was found to be 1.95 l/kWh for recycling wet-cooled coal-fired plants, 6.5 l/kWh for once-through wet cooled coal-fired plants, 0.09 l/kWh for dry-cooled coal fired plants and 0.073 l/kWh for nuclear plants. Improvements in the RWI can be achieved through the use of dry-	Valuable for input estimates.

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				cooled systems and water recycling in the case of municipal plants. It is suggested that target RWI's are set at a maximum of 2.5 l/kWh for wet-cooled coal-fired processes and 0.8 l/kWh for dry-cooled power generating processes.	
A ANALYSIS	43	1121/1/04: Whitcutt JM, Emmett RA, Ramajwe T, Mbatha Z, Humphries P, Wittekindt E Biomonitoring of wastewater	2004	Develop a rapid, low-cost human cell toxicity test that could be used for the universal monitoring of complex effluents.	Process control and analysis of WWBR, or effluent thereof
A ANALYSIS	44	961/1/99: Genthe B, Franck M, A tool for assessing microbial water quality in small community water supplies: an H2S strip test	1999	The project developed a small H2S strip test for determining water quality or contamination, aimed at small communities.	The methods developed in this paper are unlikely to be applicable to WWBRs, as more robust techniques will likely be used for water quality assessment at WWBRs.
A ANALYSIS	45	TT 405/09: Leopold P, Freese SD, A Simple guide to the chemistry, selection and use of chemicals for water and wastewater treatment.	2009	Chemistry textbook relating to water and wastewater treatment	Reference guide
A ANALYSIS / TECHNIQUE	46	KV 249/10: Garcin CJ, Nicolls F, Randall B, Fraser M, Griffiths M, Harrison STL, Development of LED-photodiode-flow cell for online measurement of dissolved substances in liquids	2010	This report describes the development of an LED-photodetector device for continuous on-line monitoring using optical flow cells as a low cost alternative to conventional spectrophotometry. Conventional spectrophotometers generally use tungsten or deuterium incandescent light sources, and have diffraction gratings, mirrors, filters and various other components that make up complex and expensive instruments. The development of light emitting diodes that emit at specific wavelengths in a narrow bandwidth offer several advantages for replacing the conventional technology: LEDs are robust, inexpensive, longer lasting, smaller, and stabilise within milliseconds. The versatility of the system developed was demonstrated in two different applications: measurement of phenolic compounds in the UV light range (280 nm) during a chromatographic purification process, and monitoring of algal cell culture density in the visible light range (465 and 760 nm) during growth in a photobioreactor. The system was controlled and monitored using Labview software, and by using flow-through optical cells, it was possible to take continuous on-line measurements as opposed to periodic sampling and external measurement. The electronic components of the system have subsequently been transferred onto printed circuit boards (PCBs) to make the system more compact. The PCBs are to be incorporated	May be of excellent use for WWBR process control and analysis. Limitations of the system were primarily that it is not possible to perform spectral scans or measure at multiple wavelengths as with conventional spectrophotometers; an LED is required to illuminate at each specific wavelength of interest. However, the use of multiple LEDs in one device can overcome this limitation. Future work will include: - Multiplexing several detectors to run on one platform - Dual and triple wavelength functionality - Design of a low cost optical flow cell that incorporates the LEDs - Low-cost fluorescence measurement - Development of the system into a hand-held probe for in-situ measurements - Signal telemetry for remote monitoring. Besides for the applications described above, future applications of the system could include: Wastewater treatment - Surface water quality - Diverse chemical and industrial processes.

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				into a new design that will be thoroughly waterproofed and will be rolled out in our lab for general bioprocess monitoring.	
A ECON	47	1568/1/12: Graham PM, Blignaut JN, de Villiers L, Mostert DJ, Sibande RX, Gebremedhin SK, Harding WR, Rossouw JN, Freese SD, Ferrer SRD, Browne M, Development of a generic model to assess the costs associated with eutrophication	2012	A generic first order model of the direct and indirect costs of eutrophication in South Africa and apply it to the Vaal Dam. The modelling was applied to estimate costs to agriculture, water treatment, property, and recreation.	Resource economics – reasoning to utilize wastewater urgently.
A ECON	48	KV 267/11: Winter D, Power Outages and their Impact on South Africa's Water and Wastewater	2011	Pumping is the most vulnerable activity in the water supply chain, but the use of gravity feeds can reduce this impact in many cases.Wastewater treatment plants with back-up power supply and overflow dams are generally not impacted by power outages... There is no doubt that power outages have had a direct impact on water and wastewater service delivery in South Africa.	Wastewater biorefineries fit with an ideology of renewable resources. This report can be expanded to look at alternative ways to provide power, in context of the biorefinery. It is unclear from the abstract if measures to reduce the impact of power outages are discussed.
A ECON	49	TT 462/10: Ginsburg AE, Crafford JG, Harris KG, Framework and manual for the evaluation of aquatic ecosystems services for the resource directed measures	2010	The National Water Resource Strategy aims to strike a balance between the use of resources for livelihoods and conservation of the resource. This process invariably requires negotiation of trade-offs. These trade-offs are principally between the resource quality on the one hand and the beneficial use of water on the other. The framework developed through this project to achieve this is explicitly congruent with methods used by DWA in the determination of Resource Directed Measures and Source Directed Controls. Definition of the benefits yielded by an ecosystem have been based on the Millennium Ecosystems Assessment framework and comparative risk assessment methodology is used to develop the causal chains linking ecological production to the defined ecosystem services. Two case studies have been developed to illustrate the framework. This Framework and Manual explores how these scenarios and their associated trade-offs should be evaluated.	Ecosystem economics, of significant relevance to WWBR, both in terms of their findings and the methodology employed.
A ECON	50	TT 442/09: Turpie JK, Wetland Valuation Volume Iii: Assessment Of The Livelihood Value Of Wetlands (TT 441/09 – 444/09)	2009		Compare wetland value with the macrophyte bioreactor
A ECON	51	KV 224/09: Musee N, Lorenzen L, Market Analysis for UASB	2009	Market analysis in South Africa of upflow anaerobic sludge blanket (UASB) technology, including suppliers, industrial users, international	This technology is potentially an integral part of any WWBR, and so analysis of the market will aid WWBR development.

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		Seeding Granules: Local and International Markets		suppliers, the South African market size, and new technologies competing with UASB.	
A ECON	52	KV 193/07: Swanepoel CM; Barnard RO, Discussion paper: Wetlands in Agriculture	2007		Possible application to WWBR macrophyte bioreactor
A ECON	53	1252/1/06: Friedrich E, Buckley CA, Pillay S, Leske A, A life cycle assessment of a secondary water supply.	2006	This study shows that a system approach as well as a process approach is needed for the integral assessment of the environmental performance in the provision of water and wastewater services. From the LCAs of individual processes involved in the provision of water and wastewater in the eThekwini Municipality, it emerged that the process with the highest contribution is the activated sludge process - used in the treatment of wastewater. However, when considering the entire system and including the losses in the distribution network for potable water, the process with the highest contribution became the distribution itself. An improvement analysis was performed and is presented. It takes into account a series of possible interventions and their consequences. Most notably, one conclusion of this study is that recycling as currently undertaken in Durban, has positive environmental impacts.	A useful approach to justify and evaluate WWBR.
A ECON	54	KV 159/04: van Zyl H, Leman A, Jansen, The costs and benefits of urban river and wetland rehabilitation projects with specific reference to their implications for municipal finance: case studies in Cape Town	2004	The document details three cost benefit case studies to evaluate the economics of rehabilitation of three wetland and river systems in the Cape Town area.	This work is not directly applicable to WWBRs, however, the methodologies used to evaluate the costs and benefits associated with rehabilitation projects could be applied to WWBRs.
A ECON	55	1383/1/04: Palmer Development Group, Economic regulation of water services in South Africa	2004	This project sought to answer how a regulatory authority determine if the average water price level is appropriate, what investment level is appropriate and how the governance model effects these two questions.	The pricing of water, as examined in this document, effects the economics of WWBRs, and so is implrtant to take into account.
A ECON	56	1077/1/02: Friedrich E, Buckley CA, The use of life cycle assessment in the selection of water treatment	2002	LCA study comparing conventional technology and membrane technology	In this study the main difficulties were experienced in the data gathering stage and they have been overcome by employing overseas data and by using calculations.
A ECON	57	TT 185/02: Palmer Development Group: So you think you want to corporatise? A guide for	2002	For the purpose of this guideline we regard the corporatisation of municipal water services as entailing the creation of a separate, legal, 'corporatised' entity, owned and governed by one or more	Limited application to WWBR, can include some insight on business model considerations for WWBR, and things to caution against, e.g. High levels of managerial autonomy can lead to over-engineering or gold-plating, especially where staff are strongly engineering-oriented.

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		municipalities considering corporatised water entities		municipalities, with the explicit objective of providing water services to some or all of the municipality's water users. The corporatised entity may enter into a range of contracts with private or public partners to facilitate service delivery.	
A ECON	58	854/1/02: Kerdachi D, The review of industrial effluent tariff structures in SA and guidelines on the formulation of an equitable effluent tariff structure	2002	...there is a need for a guideline document that provides a systematic methodology on how to formulate and implement a tariff structure that allows for an equitable proportion of finance to be provided by industry for their contribution towards the cost of effluent treatment to the required liquid and solid phase standards and guidelines of the Department of Water Affairs and Forestry (hereafter referred to as DWAF) and the Department of Health (hereafter referred to as DH) respectively and for the installation of an adequate sewerage system. This mode of operation is essential and preferable to the system of punitive measures that are not easily enforceable, nor understood by the legal fraternity usually ending up in a no win situation after months and years of protracted legal proceedings.	Minimal application to WWBR, but may be useful in justifying the WWBR approach, as one could do a cost comparison of investment vs just paying the fines. Find out if there is a more up to date document.
A ECON	59	631/1/01: Van Ryneveld MB, Marjanovic PD, Fourie AB, Sakulski D, Assignment of a financial cost to pollution from sanitation systems, with particular reference to Gauteng. (Please enclose erratum)	2001	Reference to Gauteng but can be extrapolted to use with other provinces.	Cost comparison
A ECON	60	1042/1/01: Louw GJ, Development of a solar-powered reverse osmosis plant for the treatment of borehole water	2001	This project investigated the use of a Reverse Osmosis unit, powered by solar energy, capable of producing potable water from brackish borehole feed, for rural households or small communities and demonstrated its use in field trials.	This work is not directly applicable to WWBRs, however, a comparison of the cost of producing potable water using this system versus a WWBR may inform the economics of both processes.
A HEALTH	61	1561/1/11: Roos C, Pieters R, Genthe B, Bouwman H, Persistent Organic Pollutants (POPs) in the water environment	2011	Of the 23 sites tested for dioxin-like compounds (DLCs), 77% was of industrial or semi-industrial origin, 15% was industrial-residential combinations, 6% was high-density low-income residential areas and 2% was residential-agricultural combinations.	Health concerns or unexpected factors to address in WWBR
A HEALTH	62	TT 469/11: Rodda N, Carden K, Armitage N, Sustainable Use of Greywater – Guidance Report	2011	The focus of the Guidance Document is to minimise the risks of • illness in handlers of greywater and greywater-irrigated produce, or consumers of greywater-irrigated produce. • reduction in growth or yield of plants/crops irrigated with greywater. • environmental degradation, especially reduction in the ability of soil irrigated with greywater to support plant growth.	Good guidelines for general approach in WWBR.

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A HEALTH	63	1749/1/09: Genthe B, Steyn M, Aneck-Hahn NH, van Zijl C, The feasibility of a health risk assessment framework to derive guidelines for oestrogen activity in treated drinking water	2009	A previous WRC report KV 206/08 proposed a framework to deal with endocrine disrupting chemicals for drinking water in South Africa. The framework suggests a tiered approach to screening and testing of chemicals in the water environment rather than testing for specific target chemicals and recommended the use of a trigger value for oestrogen activity.	A multidisciplinary team would need to be assembled to look at the possible sources such as industry, agriculture, waste streams etc. and follow-up samples would need to be taken to identify the specific chemicals responsible, before remedial action could be taken.
A HEALTH	64	TT 322/08: Priya Moodley P, Archer C, Hawksworth D, Leibach L, Standard methods for the recovery and numeration of Helminth Ova in wastewater, sludge, compost and urine-diversion waste in South Africa.	2008	Health concerns when dealing with wastewater and related materials as substrate	Need more work and recommendations of addressing potential health impacts of wastewater biorefineries
A HEALTH	65	1774/1/08: Burger AEC, Nel A, Scoping study to determine the potential impact of agricultural chemical substances (Pesticides) with endocrine disruptor properties on the water resources of South Africa.(EDCs)	2008	Preliminary study on endocrine disruptor pesticide contamination in SA water systems.	Report informs on the prevalence of EDSs in SA water, which could guide on the presence of EDC's in WWBR. These chemicals can affect bioconversion or final product quality or applicability.
A HEALTH	66	TT 298/07: Genthe B, Knoetze M, Management of water-related microbial diseases: Volume 4: How dangerous is the problem?- Communicating the risk	2007	This guideline presents how best South Africans can protect themselves from water-related microbial diseases and provides a framework of principles and guidelines for the communication of health risks, specifically for water service providers.	If WWBRs are to be potable water producers, then this dicument will inform how best to communicate the potential health risks associated with recovered water.
A HEALTH	67	1439/1/06: Austin LM, Phasha MC, Cloete TE, Pathogen destruction in urine diversion sanitation systems: Vol 1	2006	This document discusses ecological sanitation by means of a literature review and examines processes taking place in the vault of a urine-diversion (UD) toilet focussing on pathogen destruction parameters as well as appropriate practices for faeces collection and disposal.	Limited applicability in WWBRs, however, the pathogen destruction process described could inform parallel processes in WWBRs.
A META	68	2199/1/12: Pouris, Anastassios, A Pulse Study on the State of Water Research and Development in South Africa	2013	A quantitative account of key R&D trends in the water sector. The analysis identifies that the field is performing above expectation in comparison with the country's research size.	Overview of the research landscape in South Africa with regards water. However, little attention has been paid to the increasingly important water reuse/recovery/beneficiation concepts.
A META	69	TT 503/11: Winter D, Bangure K, Water-related research projects in Agriculture undertaken in South Africa	2011	develop a database of all water-related research projects in agriculture being undertaken in South Africa during 2010	General overview of agriculture specific water research in 2010.

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A META	70	TT 513/11: Keith BA, Water Resources of South Africa, 2005 Study (WR2005): User's Guide (Version 2, November 2011)	2011	A revised appraisal of the Water Resources of South Africa. Enhancements to the WR2005 system, using the information from existing WR2005 calibrations to patch and calibrate streamflows for all 19 water management areas.	General overview of water resources. Gives an estimate of the water supply problem, which is a reason for this research.
A META	71	KV 277/11: Pollard S, Du Toit D, Biggs H, A guide to complexity theory and systems thinking for integrated water resources research and management	2011		Possible overview angle
A META	72	TT 488/11: Balfour F, Hanlie Badenhorst H, Trollip D, A gap analysis of water testing laboratories in South Africa	2011	Developed a database of existing laboratories that undertake water quality testing and, through a survey, obtained information on their capability and credibility to determine capacity gaps.	Water analysis laboratories in SA provide a crucial capacity, to analyse the inputs and outputs of potential WWBRs, particularly with regards potable water production. This database provides information on this.
A META	73	TT 514/11: Claassen M, Funke N, Nienaber S, The Water Sector Institutional Landscape by 2025	2011	Project to build knowledge about key drivers and uncertainties related to SA water sector institutions, with a focus on water resource management.	WWBRs can feed into water resource management as a water source, thus this report outlines some key stake holders in the space.
A META	74	1547/1/10: Cloete TE; Gerber A, Maritz L, Inventory of water use and waste production by industry, mining and electricity generation	2010	The overall objective of this project was to compile a first order inventory of the amount of water used and effluent produced by the South African industrial, mining and power generation sectors, and to assess the impact these might have on water quality, but existing data sets were of limited value and outdated.	It is of great concern that many of the surveyed industries do not conduct any chemical analyses on the effluents that they produce and that where chemical analyses are done, they very seldom go beyond a few basic parameters like COD, phosphate and nitrate. The current data therefore merely indicates a trend rather than enabling the user of the data to determine the exact pollution load to the environment. As there are currently no standard requirements in place for municipal councils with regard to effluent monitoring, it is recommended that such a standard be developed and implemented in order to obtain more accurate information on the chemical composition of the effluent.
A META	75	TT 450/10: Boyd LA, Tompkins RL, Heath RGM, Integrated water quality management: a new mindset	2010	Integrated water management	Contextualize.
A META	76	TT 417/09: Malzbender D, Earle A, Deedat H*, Hollingworth* B, Palesa, Review of Regulatory Aspects of Water Services Sector	2009	Review of water regulations. Covering international best practice and theory, local legislature, and costing models. Legislature seeks to control potability of water, and prevent non-compliance (ie release of sewage etc).	Legislature will apply to WWBRs, and so this document would inform operating conditions and comliance.
A META	77	TT 267/08: Pott AJ, Benadé N, Pieter van Heerden P, Grové B, Annadale JG, Steyn M,	2008	Technology transfer and integrated implementation of water management models for agriculture and water managers.	Some of these models could inform WWBR flows and aid inunderstanding WWBR systems. However, it is likely some adaptation of existing models would be required.

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		Technology transfer and integrated implementation of water management models in commercial farming.			
A META	78	TT 366/08: Frost & Sullivan, Membrane-related Water Research Impact Assessment	2008	Assessment of research relating to membranes used in water treatment. List of WRC funded projects on membrane-related water research from 1993 -2011 (66 reports)	Starting point to look at membrane technology in WWBR
A META	79	1671/1/08: de Swardt BW, Barta B, A First-Order National Audit of Sewerage Reticulation Issues	2008		Big picture
A META	80	1605/1/07: van Zyl JE, and Geusteyn LC, Development of a National Water Consumption Archive: (Only available on CD)	2007		
A META	81	1213/1/05: Vosloo R, Bouman H, Survey of certain persistant organic pollutants in major South African waters (POPS)	2005	countrywide assessment of POPs in a selection of major water bodies, and would indicate geographical areas (such as industrial and or residential) where more concerted action, management or research needs to be focussed.	WWBR might take special care to develop knowledge or something to degrade these throughout the process stream
A META	82	TT 226/04: Conningarth Economists, Research impact assessment: Lessons to be learned from the cost-benefit analyses of selected WRC research projects.	2004	A sample, consisting of six research projects, was selected and evaluated by means of Cost-Benefit Analysis (CBA). These projects were the following: - ACRU Model Development - Hydrosalinity System Models - Surface Water Resources of South Africa - Biological Nutrient Removal - Dry Cooling in Power Generation - Combined Services Model	Provides insight from the overall gap analysis for a development plan for WRC-funding of WWBR research. ... the following policy and planning directives for future WRC research initiatives are proffered: - The CBA provides unequivocal evidence that the WRC research outputs have made a significant contribution to improving the economic welfare of South Africa - The growing importance of research projects dealing with water conservation and demand management is in line with the WRC's strategic focus and the government's development prerogatives - Agriculture remains the largest water user and, therefore, requires that a substantial amount of resources still be devoted to research activities that would promote more efficient use of water for irrigation purposes. However, the CBA results also show that research for other users is of great significance because of the potentially higher returns that can be expected on such outlays. - The CBA shows that research into new technologies and the

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					transfer thereof to the operational level provides handsome dividends. On the other hand, research projects which assist in the better planning of water projects in all their facets also produces more than reasonable returns. - The CBA results of the projects in question show that proportionally larger benefits can be obtained from research directed at reducing operational costs. This is despite the fact that, in some cases, such reductions go hand-in-hand with major capital expenditure.
A META	83	1185/1/04: Swartz CD, Ralo T, Guidelines for planning and design of small water treatment plants for rural communities, with specific emphasis on sustainability and community involvement and participation.	2004	The aims of this project included to create an understanding of the unit processes employed in small rural (drinking) water treatment plants, and to provide information on indigenous water treatment technologies.	Project included a workshop which can guide the WWBR data gathering workshop planning. Report has minimal relevance to WWBR.
A META	84	TT 115/99: DWAF, WRC, A framework for implementing non-point source management under the National Water Act	1999	The research set out to examine how best to implement the Water Act in terms of non-point water source management.	The legislature outlined in the Water Act will bind water production in WWBRs, and so this document may assist in assessing legal compliance in WWBRs.
A META	85	629/1/96: Palmer Development Group, Evaluation of solid waste practice in developing urban areas of South Africa: Executive Summary	1996	The focus of the report was to assess the factors which effect solid waste management, specifically in developing communities.	Limited applicability to WWBRs.
A META	86	561/1/94: Palmer Development Group, Water and sanitation in urban areas: Survey of on-site conditions	1994	Drinking water - Water supply, Sanitation - On site sanitation	Background information
A SOLIDS	87	1745/1/12: Still DA, Foxon KM, Understanding sludge accumulation in VIPs	2012	Disposal of dense pit sludge at wastewater treatment works has been found to quickly overload the works in addition to being counterproductive in a number of respects. The policy of the South African government stresses the value of human excreta as a resource although utilisation must be done within strict parameters due to the hazards of contamination. Most pits are filling in five to nine years. Pits generally fill at a rate of 40 litres per capita annum, with 60 litres per capita annum providing a safe margin for planning pit design and emptying programmes.	This gives an estimate input for a potential WWBR based on solid wastes.

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A SOLIDS	88	KV 248/10: Lutchamma-Dudoo C, Biologically Enhanced Primary Settlement:	2010	Investigation into using biological agents as settling agents to replace the more commonly used ferric chloride, to allow rural communities to become more self relient with regards wastewater treatment.	The technology could be applied in WWBRs, although its capabilities and limitations need to be further explored.
A SOLIDS	89	1524/1/07 Carden K, Armitage N, Winter K, Sichone O, Rivett U, Understanding the use and disposal of greywater in the non-sewered areas in South Africa.	2007	Situation analysis: Understanding the use and disposal of greywater in the non-sewered areas in South Africa.	More work required to contextualize (modular) wastewater biorefinery units in non-sewered areas – starting with a feasibility study, then with solid substrate bioprocess technologies
A SOLIDS	90	1550/1/07: Broadhurst JL, Hansen Y, Petrie JG, Waste Characterisation and Water-Related Impact Predictions for Solid Mineral Wastes: a new approach	2007	The need to improve the way in which solid mineral wastes are characterised is driven not only by the limitations in terms of current databases and methodolodies for the generation of such. There is also a requirement for a more systematic and rigorous approach which will ensure that the necessary data and information is integrated into the decision stages of a project life cycle in a time and cost effective manner. This project aimed to develop a generic and integrated methodology for predicting water-borne environmental impacts associated with solid mineral wastes.	Not directly relevant to WWBR, but the approach and methodology may be informative. The increased understanding afforded by this approach provides opportunities to influence and control behaviour, and eventually optimise waste management and minimise environmental imapcts across the entire life cycle of minerals operations.
A SOLIDS	91	1240/1/04: Marx CJ, Alexander WV, Johannes WG, Steinbach-Kane S, A technical and financial review of sludge treatment technologies	2004	The aim was to give a clear indication to metropolitan councils, municipalities and other sludge producers of the technologies available and applicable under local conditions, as well as an indication of the cost and economy of scale applicable to each process. The study includes an overview of current sludge management practices in South Africa, as well as an estimate of sludge quantities and qualities and a brief description of commonly used sludge treatment and disposal methods.	Applicable to sludges used/produced in WWBR, including the legal framework, using as a basis the Sludge Utilisation or Disposal Decision Flow Diagram (SUDDFD), as presented in the Addendum No 1 to the Permissible Utilisation and Disposal of Sewage Sludge (Edition 1), (Department of Agriculture et al 1997). The sludge treatment requirements and available technologies for each of the utilisation or disposal routes are listed in matrix form for easy reference and use. Also see if there are updated on this work.
A SOLIDS	92	1167/1/03: Schoeman JJ, Steyn A, Slabbert JL, Venter EA, Treatment of landfill leachate from hazardous and municipal solid waste	2003		
A SOLIDS	93	544/1/00: Norris GA, Sludge build-up in septic tanks, biological digesters and pit latrines in South Africa (ONLY PHOTO COPIES AVAILABLE)	2000		
A SOLIDS	94	TT 107/99: Ceronio AD, Van Vuuren LRJ, Warner APC: Guidelines for the design and	1999	Sludge drying / 'preprocessing'	Needs further work to consider drying beds as solid substrate bioreactors

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		operation of sewage sludge drying beds			
A SOLIDS	95	599/1/99: Pearson I, La Trobe B, Co-disposal and composting of septic tank and pit latrine sludges with municipal refuse	1999	Sludges cannot in general be simply composted on their own. It is necessary to ensure that pasteurization temperatures are achieved during the composting process to ensure that pathogenic organisms are eliminated, and weed seeds are made non-viable. To achieve such temperatures the following conditions are required: • A bulking agent to maintain pores and channels throughout the compost windrow for the continuous penetration of oxygen. • A method of promoting the flow of air through the window to support the active organisms responsible for the breakdown of the organic matter. • An insulating layer on the surface of the window to maintain internal temperatures and to trap malodours. In the tests carried out in this project, domestic refuse, garden refuse, and grass cuttings were used as bulking agents, and wood chips were used to cover and insulate the heaps or windrows. The project includes prelminary costing.	Large WWBR potential, specifically for best practice in SSF/biosolid bioprocesses. What has been done since the publication of this report? The report recommends further evaluation of "passive" aeration systems for compost windrows employing sewage sludge, which could be of use to WWBR as well.
A SOLIDS	96	391/1/96: Novella PH, Ross WR, Lord GE, Greenhalgh MA, Stow JG, Fawcett KS, The co-disposal of wastewater sludge with refuse in sanitary landfills	1996	Sanitary landfilling, whereby the waste is compacted and covered each day with a soil layer offers the most versatile method for the disposal of solid wastes in an economical and environmentally sound manner. Co-disposal (or joint disposal) in its widest sense, is understood to be the calculated and monitored interaction of wastewater sludge (or selected difficult industrial and commercial wastes) with municipal refuse in a properly controlled landfill site. ... difference perceptions of the values and dangers of the co-disposal practice have developed. The experimental runs established that excessive addition of sludge liquor caused the belly plate of the landfill compactor to sink too deep into the refuse-sludge mixture, thus retarding the manoeuvrability of the machine. The Safe Working Ratio of refuse to sludge liquor (by volume) for the winter and summer seasons was determined to be 6:1 and 4:1 respectively. The importance of moisture in solid-state anaerobic decomposition has been highlighted for optimising the physical, chemical and biological conditions for accelerated stabilisation of the landfilled waste. ... such an integrated waste management strategy would be advantageous in terms of improved pollution control.	Can this be interpreted for supplementary resources (e.g. lignocellulosic/organic biomass) for WWBR? Is this current practice, or is this report out of date?

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A?	97	1128/1/03: Naidoo V, Buckley CA, Survey and preliminary investigation into biodegradation of pesticide wastes	2003	The project outlines a comprehensive schedule of pesticide use and waste generation in Southern Africa as well as a comprehensive survey of existing technologies for the disposal of pesticides.	Limited applicability to WWBRs, although some pesticide treatment methodologies may be relevant if WWBRs are to treat pesticide wastes.
A2	98	TT 568/13: Ralivhesa K, van Averbeke W, Siebrits F, Production Guidelines for Small-Scale Broiler Enterprises	2013	Data or contacts of poultry wastewater?	
A2	99	1734/1/13: Brouckaert CJ, Mhlanga F, Arnold, Quantitative Assessment of Industrial effluents for discharge to sewer	2013	Quantitative approach to industrial effluents	
A3 HEALTH	100	TT 559/13: Herselman JE, Guideline for the Utilisation and Disposal of Water Treatment Residues	2013	Guidelines that describe the requirements for the disposal and/or use of water treatment residues.	WTRs can be used, and are products of WWBRs. The guidelines on their use and disposal could strongly influence WWBR set up and operation.
A3 HEALTH	101	TT 561/13: Masoabi D, Boyd LA, Thomas Coughlin T, Heath RGM, Endocrine-Disrupting Compounds - Sampling Guide. Volume II	2013		Analysis methods.
A4 ECON	102	KV 307/09: Naidoo D, Moola S, Place H, Discussion paper on the role of water and the water sector in the green economy within the context of the new growth path	2013	Literature review, and interview based research on the role of water in the green economy, and the economy in general (in as much as many sectors are heavily dependant on water).	This work contextualises the need for WWBRs, and the development of WWBRs can be placed in the green economic scenario.
A4 META	103	2075/1/13: Pegram G, Baleta H, Water in the Western Cape Economy	2013	This project investigates possible ways of assessing regional water resources in the Western Cape system (Berg and Breede-Overberg WMAs) from a political-economic and developmental perspective. Increasingly stressed water resources and the uncertainty of climate and development futures have highlighted the close interactions between water, energy and food security at a national level.	The project acknowledges that data throughout this project has been a challenge. Perhaps further work on WWBR can improve this case, and vice versa. An in-depth analysis of local level water in the economy implications is required. This is because initial presentations of this work have found the engagement with the private sector less compelling due to the scale of water and economy investigated (district level municipality or water management area). The same is expected to be the case for WWBR.
A4 META	104	1890/1/12: Duncker LC, CSIR, Establishment of a sanitation technology demonstration centre	2012	The concept, along with WADER – Water technologies demonstration programme (http://wader.org.za/), carries great potential to further applied studies and application towards the WWBR concept. See also http://www.csir.co.za/Built_environment/santechcentre/	Due to this project being in its infancy, little information was found regarding this.

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A5 ECON	105	TT 543/12: vd Merwe-Botha M, Quilling G, Drivers for wastewater technology selection: Assessment of the selection of wastewater treatment technologies by municipalities in relation to the management capability and legislative requirements	2012	A sobering observation of the constraints municipalities face when selecting treatment technologies, that highlight the challenge of wastewater biorefineries in this context.	More work required on how these factors are affected when an economic business case for bioproduction applies, e.g. would a privately managed plant be a better option.
A5 ECON	106	1805/1/12: Grové B, Frezghi M, Pott A, Lecler N, Development and testing of an integrated hydro-economic model	2012	Model linking hydrologic simulation with the economic optimisation to quantify possible impacts of changes in catchment water management scenarios.	Modelling could be used to quantify economics used in WWBRs, particularly in reference to water.
A5 META	107	2170/1/13: Siebrits R, Winter K, Identifying and Prioritising Water Research Questions for South Africa	2013	A new era in water research in South Africa began with the promulgation of the Water Research Act No. 34 of 1971. The Act led to the formation of the Water Research Commission (WRC) and the Water Research Fund with the purpose of initiating, managing and financing water research. This study commences with the identification of the prevailing paradigms that have influenced the history of water research in South Africa by analysing the publication output over the last four decades and in identifying research questions proposed by a range of researchers active in the water sector in South Africa.	A good overview of water related research In South Africa. This study needs to expand on this selection with regards to relevance to WWBR.
B		2144/1/14, Swanepoel C, Bouwman H, Pieters R, Bezuidenhout C, Presence, concentrations and potential implications of HIV-anti-retrovirals in selected water resources in South Africa		Develop extraction and analytical procedures for selected HIV-ARVs from water and fish.	The inflowing and outflowing concentrations over time on a range of different WWTPs with different efficiencies (based on Green Drop data) needs to be determined.
B		Technical note 3139: Myburgh PA; Lategan EL; Howell CL, Infrastructure for irrigation of grapevines with diluted winery wastewater in a field experiment	2015	Relatively simple infrastructure and procedure required to dilute the winery wastewater to COD levels ranging between 100 and 3 000 mg/ℓ in 15 m3 tanks	Scale up studies
B		1881/1/14: Myburgh PA and Howell CL, The impact of wastewater irrigation by wineries on soils, crop growth and product quality	2014	The possibility of re-cycling winery wastewater for vineyard irrigation was investigated in a field trial near Rawsonville in the Breede River Valley. Wastewater obtained from a co-operative winery was augmented to levels of 100 mg/L, 250 mg/L, 500 mg/L, 1000 mg/L,	The COD must be augmented to 3000 mg/L or less, preferably to less than 2000 mg/L to avoid unpleasant odours while irrigations are applied. Due to the possibility that direct contact with winery wastewater may cause off-odours in the wine, overhead sprinkler irrigation is not recommended if winery wastewater is

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				1500 mg/L, 2000 mg/L, 2500 mg/L and 3000 mg/L chemical oxygen demand (COD)	re-used for vineyard irrigation.
B	108	1942/1/13: Budhram S, Nyuswa M, Rajagopaul R, Thompson P,Operational and design considerations for high rate clarifiers in the South African water treatment industry	2013	high rate clarification technology was evaluated based on investigations conducted on a 500 m3/day demonstration model HR CSAV high rate clarifier	will assist water treatment designers and water treatment practitioners particularly in South Africa to make informed decisions on the appropriateness of high rate clarification processes under local conditions.
B	109	2005/1/12: Pocock G, Joubert J, Optimisation of Waste Stabilisation Ponds	2012	Waste Stabilisation Ponds using duck-weed	Waste stabilization ponds can be used for nitrogen removal and concentration in biomass from wastewaters. Duck-weed allows continual removal of biomass (as opposed to algae ponds), which could potentially be applicable to WWBRs.
B	110	1936/1/11: Burton SG, Welz PJ, Ramond J-B, Sheridan G, Kirby B, Schueller A, Rodriguez A, Pather-Elias S, Prins A, Cowan DA, Health for purpose in constructed wetlands	2011	Constructed wetlands to treat high COD winery wastewater	Molecular biology tools to assess the health of constructed wetlands, microbial community changes and the impacts of interventions (such as fertilizer addition). CWs are applicable to the polishing of wastewaters, potentially in WWBRs.
B	111	1658/1/11: Schoeman JJ, Sekgwela EI, Hallis D, South African clinoptilolite for the removal of NH3-N from secondary sewage effluent	2011	This project investigated the potential of reducing ammonia-nitrogen via inclusion of a selective ion-exchange system to the existing treatment train. Biological nitrification and algal ponds may not be suitable where low temperatures are encountered. Stripping and breakpoint chlorination are considered to be too expensive for the high ammonia-nitrogen concentration levels encountered in secondary effluent. Selective ion-exchange of ammonia-nitrogen using the natural zeolite, clinoptilolite, in the sodium form, which is not very sensitive to temperature fluctuations, and which is a locally occurring mineral, should be a suitable material for ammonia-nitrogen removal from secondary sewage effluent. Thus, the main aim of this investigation is to develop process design criteria and costs for the implementation of a South African clinoptilolite for ammonia-nitrogen removal from secondary effluents for pollution control.	Limited applicability in WWBRs, however, the concept of using local materials to improve the plant's operation could inform parallel processes in WWBRs.
B	112	1669/1/09: van der Merwe IW, Lourens A, Waygood C, Innovative approaches to brine handling	2009	Today, typical water recovery rates for different applications are: 40-45% for Sea water desalination, 70-85% for Industrial effluent and 85-90% for brackish water desalination. The major research effort in high recovery systems for in-land brackish water and industrial systems is in the region above 95% water recovery. The project investigated and identified innovative approaches to brine and sludge management; These innovative concepts were then compared with	Good guiding report on using brines in the WWBR context. Collected data about the present brine and sludge volumes in South Africa in an appropriate database. Volumes and sources of brine and sludge were determined through a survey of industry. For this survey, 268 companies were contacted, of which 185 positive responses were received. Despite the good response rate (69%), the development of a detailed database was

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				current best practises in order to identify those concepts which should be investigated further; For the promising concepts, a more detailed evaluation was performed in order to identify those with highest potential. Concepts evaluated include the 'WAIV' system, freeze desalination, and dewvaporation.	hampered by either a lack of data within some organizations, or an unwillingness to release detailed data due to commercial and other sensitivities... A total of just over 530 000 kl/d of effluent is discharged to inland systems, containing approximately 1060 t/d of salt (refer to the table in report). The report inclues a list of potential by-products from South African mine water.
B	113	1079/1/08: Loewenthal RE, Morgan B, Lahav O, Hearne G, Research on an Investigation into sulphur chemistry with specific application to biological sulphate-removal processes	2008	The principal aims to this contract were threefold: i. to investigate and model a sulphide chemistry in both the aqueous and gaseous phases, ii. to investigate and model the recovery of elemental sulphur through chemical oxidation of sulphide, and iii. to investigate and model the precipitation and recovery of metals.	The research presented in this report must be considered as a preliminary study into feasibility of applying biological – physical – chemical treatment processes to AMD waters.
B	114	TT 193/07: Rose PD, Hart OO, Dekker LG, Clark SJ, Integrated algal ponding systems and the treatment of domestic and industrial wastewaters: part 4: Report 7	2007	Initial studies in the production of high-value bio-products from halophilic micro-organisms in wastewater beneficiation using integrated Algal Ponding Systems.	The application of halotolerant microorganisms to WW treatment is extremely applicable to WWBRs, and this work should inform any WWBR work that considers saline compositions.
B	115	1544/1/07: Burton SG, Sheridan C, Law-Brown J, le Roes M, Cowan D, Rohr L, Mashapu N, Integrated research for use in constructed Wetlands for Treatment of Winery Wastewater	2007	Constructed wetlands for winery wastewater	Research applicable to the final polishing of wastewater treated in WWBR. More work in needed to characterize the applicability with a range of wastewater compositions.
B	116	971/1/07: OV Shipin OV, Meiring PGJ, Transforming the Petro Process for Biological Nutrient Removal	2007	Transforming an existing process to fulfill new functions	Can this process and/or methodology be adapted to bioproduction
B	117	763/1/07: Lew C, Biotechnological approach to the management of effluents from the Pulp and Paper Industry.	2007	Biological methods (white rot fungi and hemicellulytic enzymes) are used to treat effluent.	Application to WWBR. Lab scale - needs scale up
B	118	1539/1/06: Gaydon P, McNab N, Sahibdeen M, Pillay I, Mulder G, Thompson P, Evaluation of	2006	The simplest low technology units are anaerobic treatment systems such as septic tank and soil drains … Requirements for greater degrees of sophistication progressively bring in engineered pond and	Package plants most often fail in their ability to effectively nitrify ammonia and in disinfecting against bacteria, due to faults in design and operation, not due to the process technology per se. More work

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		Sewage Treatment Package Plants for Rural, Peri-Urban and Community use		wetland treatment systems, trickling filters, rotating biological contactors and mechanically aerated treatment systems.	required to evaluate the suitability of these package plants for modular use in wastewater biorefineries in communities. - link up with SEWPACKSA?
B	119	1361/1/06: Burton SG, Cowan DA, Garcin C, van Schalkwyk A, Werner C, A customised bioreactor for beneficiation and bioremediation of effluents containing high value organic chemicals.	2006	The development of the bioreactor was based on understanding of bioremediation of polyphenolic wastewaters, with the additional design and assembly of the components required for recovery of phenolic derivatives from treated effluents using hydrophobic membranes. In this project they developed technology to facilitate the extraction of hydrotyrosol from table olive wastewaters produced in the western Cape, and then to bioremediate the residual extracted wastewater.	A good example of producing valuable chemicals from wastewater - potential unit process in WWBR.
B	120	1364/1/06: Sigge GO, Britz TJ, McLachlan T,van Schalkwyk N, Treatment of apple and wine processing wastewaters using combined UASB technology and ozonation scenarios.	2006	Treatment of apple and wine processing wastewaters using either UASB or a combination of ozonation and UASB technologies. Report includes conclusions on cost efficiency of technologies.	This work is applicable to WWBRs, particularly if UASB technologies are going to form part of the process. It demonstrates UASB use with specific wastewaters, and this must be extended to include other wastewaters.
B	121	1338/1/05: Soteman SW, Ristow NE, Loewenthal RE; Wentzel MC, Ekama GA, Integrated mass balance models for chemical, physical and biological processes in wastewater treatment plants: Part One	2005	Integrated mass balance models for chemical, physical and biological processes in wastewater treatment plants: making wastewater biorefineries possible in principle.	More work required to adapt these mass balance models for wastewater biorefineries – product focused
B	122	1348/1/05: Heath RG, Coetser SE, Molwantwa J, Rose PD, Implementing the degrading packed bed reactor technology and verifying the longterm performance of passive treatment plants at Vryheid coronation	2005	The report details the long term full scale operation of a passive treatment method for acid rock drainage.	The research may be applicable in WWBRs, if the biorefinery is to treat acid rock drainage.
B	123	TT 195/04: Rose PD, Corbett CJ, Hart OO, Whittington-Jones KJ, Salinity, sanitation and sustainability: Report 9 (Rhodes BioSURE process: biodesalination of mine drainage wastewaters)	2004	biodesalination of mine drainage wastewaters	Relevance to WWBR of industrial (mine) wastewaters

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B	124	1084/1/04: Suruijal S, Tivchev G, Kasan HC; Bux F, Development of biological treatment technology for the remediation of edible oil effluent.	2004	The edible oil industry has been identified to be amongst the 75 industrial groupings in South Africa. In all, there are about 16 edible oil-processing plants, run by 10 separate groups. These industries refine and process approximately 300 000 tons of crude vegetable oil per year, which increases annually by about 3%. The objectives of the research included: • To investigate the source of effluent production during the different stages of refining • To chemically characterise the effluent. A preliminary costing analysis was also performed.	This report provides information on input streams to WWBR, and potential technologies to beneficiate them. The oil effluent was found to contain amounts of phytosterols, which could possibly be extracted, purified and sold as an animal feed supplement. An additional area identified is the need for a comprehensive analysis of the effluent. Settling problems as well as changes in microbial interspecies interactions have been noted in the pilot-scale activated sludge system.
B	125	1172/1/04: Rajagopaul R, Pillay VL, The evaluation and design of sludge dewatering and water filtration systems using tubular woven fabric technology	2004	Technology can be used in WWBR	DSP
B	126	1243/1/03: Van Hille RP, Antunes APM; Sanyahumbi D, Nightingale L, Duncan JR Development of integrated biosorption systems for the removal and/or recovery of heavy metals from mining and other industrial wastewaters and determination of the toxicity of metals to bioremediation processes	2003	Removal and recovery of heavy metal from mining and other industrial wastewaters. Pilot scale	Much of the methodology and research approach can be applied to the WWBR concept.
B	127	616/1/03: Duncan JR, Stoll A, Wilhelmi B, Zhao M, van Hille R, The use of algal and yeast biomass to accumulate toxic and valuable heavy metals from wastewater	2003	This project focussed on determining the efficiency and capacity of different types and forms of microbial biomass in removal of heavy metals from wastewaters generated by mining, electroplating, battery, tannery and other industries.	The application of heavy metal removal from wastewaters may be important in WWBRs, if WWs with a high heavy metal content are to be treated.
B	128	845/1/03: Antunes APM, Sanyahumbi D, Nightingale L, Payne R, Maclear A, Duncan JR, Development of bioreactor systems for the treatment of heavy metal containing effluents	2003	This report set out to evaluate the potential of algae and the water fern Azollu to accumulate heavy metals from effluents as well as exploit the exopolysaccharide production of a number of algae to improve metal removal efficiencies and from there optimise bioreactor design for metal removal on site.	The application of heavy metal removal from wastewaters may be important in WWBRs, if WWs with a high heavy metal content are to be treated. This technology would inform that unit process.
B	129	846/1/03: Brozel VS, Development of a continuous flow	2003	The aim of the project was to develop technology for the biodegradation of hydrophobic pollutants by emulsification using a	Investigate the use of rhamnolipid production in the WWBR context.

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		membrane bioreactor catalysing the solubilisation of hydrophobic pollutants by rhamnolipid-producing bacteria		membrane-supported biofilm producing the surfactant rhamnolopid produced by Pseudomonas aeruginosa.	
B	130	970/1/02: Hu Z, Sötemann SW, Vermande SM, Moodley R, Little C, Lakay MT, Wentzel MC, Ekama GA, External nitrification with the aid of fixed media trickling filters (TF) to increase the capacity of biological nutrient removal (BNR) suspended medium activated sludge (AS) systems	2002	External nitrification with the aid of fixed media trickling filters	An example of a bioreactor system likely to be suitable to the biorefinery. Needs further investigation
B	131	836/1/02: Coetzee PP, Meyer J, Evaluation and development of physical water treatment processes for the reduction of CaCO3 scale	2002	The focus was on the fundamental chemistry and physics of the processes involved in physical water treatment, the development of experimental and analytical methods to study the effects of physical fields on systems where scaling can occur, and the formulation of theoretical models to explain the mechanisms involved.	Limited application to WWBR, but included as an example/reminder to consider physical water treatment processes - both as an opportunity and a risk.
B	132	934/1/01: Van Heerden J, Ehlers MM, Korf C, Cloete TE, Active biomass fraction of MLSS and its role in biological phosphorus removal	2001	The report examines biological phosphorous removal in activated sludge WW treatment, modifiying a number of process variables to achieve maximum phosphorous removal.	Phosphorous removal will be an important part of WWBRs, and so this report can inform process considerations around that, however futher work in applying this technology to WWBRs is needed.
B	133	802/1/01: Dill S, Cloete TE, Coetser L, Zdyb L, Determination of the suitability of alternative carbon sources for sulphate reduction in the passive treatment of mine water	2001	to develop a quick test method for the assessment of potential carbon sources regarding their suitability for use in passive treatment systems for the use of sulphate reduction in small-scale anaerobic reactors.	the release of carbon from complex carbon sources over time to more fully understand the sustainability of carbon release from potential carbon sources.
B	134	822/1/00: Drysdale GD, Atkinson BW, Mudaly DD, Kasan HC, Bux F, Investigation of the microbial contribution to nutrient removal in an activated sludge wastewater treatment process	2000	Investigation of the microbial contribution to nutrient removal in an activated sludge by conducting a microbiological and plant parameter survey at different sites of WW treatment, and establishing the extent of correlation between microbial predominance and nutrient removal in different reactors.	The methodology used in this research is readily applicable to WWBR reactors, and would allow for tighter control of operations, and better uunderstanding of process parameters.

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B	135	933/1/00: Ntshudisane BM, Oosthuizen DJ, Ehlers TE, Cloete TE, Biolog for the determination of microbial species diversity and evenness in activated sludge systems	2000	Process analysis	Can this be adapted to be used in process control and analysis in WWBR
B	136	688/1/97: Bux F, Atkinson BW, Kasan HC, Laboratory and pilot-plant bioreactor development for remediation of metal-contaminated wastewater using activated sludge as biosorbent	1997	Remediation of metal-contaminated wastewater using activated sludge as biosorbent	Evaluate the impact of this work to metal-containing WWBR
B	137	427/1/95: Smollen M, Kafaar A, Development of electro-osmotic sludge dewatering technology	1995	Electro-osmotic sludge dewatering was found to be more effective than mechanical dewatering in the case of chemical gelatinous or biological fine particle sludges.	Work done was purely theoretical – no large scale electro-osmotic sludge dewatering plant existed at the time of the study. This work therefore needs to be validated before its aplicability to WWBRs can be assessed.
B	138	357/1/94: Bux F, Swalaha FM, Kasan HC, Microbiological transformation of metal contaminated effluents	1994	to develop cheaper, effective biosorbents to treat industrial wastes contaminated with metals.	Scale up needed
B	139	327/1/90: Nell JH, Van der Merwe M, Barnard RO, Evaluation of the active sewage pasteurisation (ASP) process for the treatment of sewage sludge	1990	Provides a method to detoxify sewage sludge such that it is suitable for unrestricted horticulture and agricultural use as a fertilizer.	More work required to determine if method is suitable for applications other than treating the sludge generated from dilute municipal sewage.
B	140	520/1/01: Pearson IA, Bhagwan J, Kariuki W, Banda W, Guidelines on appropriate technologies for water supply and sanitation in developing communities		Social aspects – community involved WWTW	Not really relevant
B AD		2105/1/14: Aoyi O; Apollo SO; Akach JWJP; Pete KY, Integrated photo-catalytic and anaerobic treatment of industrial wastewater for biogas production	2015	The treatment of high strength wastes such as molasses, textile, heavy metals and pharmaceutical waste water was investigated under different experimental conditions. An Integrated AD and Advanced oxygenation process (AOP) using South African zeolite was applied in the treatment of methylene blue dye in up-flow fixed bed bioreactor and UV photoreactor.	High cost of UV- rather use sunlight. Photodegradation of wastewater with high colour intensity difficult.
B AD	141	1538/1/09: Buckley AC Brouckaert CJ, A Feasibility Study	2009	Industrial wastewater, business model.	More work required to adapt this to include additional products in wastewater biorefinery context.

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		in eThekwini Municipality on Anaerobic digestion for the Treatment of Toxic and High Strength Organic Wastes: A Study of the Business Case of Treating High Strength Industrial Wastes			
B AD	142	1216/1/05: Loewenthal RE, Ristow NE; Soteman SW; Wentzel MC; Ekama GA, Hydrolysis of primary sewage sludge under methanogenic, acidogenic and sulfate-reducing conditions,	2005	This report details the technical outcomes of investigatoins into the hydrolysis of primary sewage sludge, in order to produce accesible carbon for use in the BioSURE process which treats acid rock drainage.	The technology is applicable to WWBRs in the case where the WWBR treats ARD as well as sewage.
B AD	143	762/1/04: Sacks J, Buckley CA, Anaerobic digestion of high-strength or toxic organic effluents in available digester capacity.	2004	This project investigated the utilisation of available anaerobic digester capacity in KZN for the treatment of high-strength or toxic industrial effluents.	This work is applicable to WWBRs in as much as anaerobic digesters will likely form a key process within WWBRs, however this work covers a very specific area and question, and will need to be expanded upon to prove larger applicability.
B AD	144	455/1/01: Strydom JP, Mostert JF, Britz TJ, Anaerobic digestion of dairy factory effluents	2001	This research programme surveyed South African dairy industry to determine the present situation, requirements and need for effluent treatment; and investigated the use of anaerobic digestion of dairy wastewater.	Anaerobic digestion will likely form a key process in WWBRs, and so this report on ADs use for this specific application can inform that.
B AD	145	189/1/92: Division of Water Technology CSIR, Milnerton Municipality, University of Cape Town, Afrox Ltd, Evaluation and optimisation of dual digestion of sewage sludge. Executive Summary (and 189/2/92, 189/3/92, 189/4/92)	1992	Evaluation and optimisation of dual digestion of sewage sludge using an autothermal thermophilic aerobic reactor first stage and a mesophilic anaerobic digester second stage.	Analysis and modelling of the effect of industrial effluents discharged to municipal WWTWs. This work can be applied to WWBR in integrated municipal/industrial wastewaters.
B AD	146	87/1/84: Trim BC, Sludge stabilisation and disinfection by means of autothermal aerobic digestion using oxygen	1984		
B ALGAE	147	TT 390/09: Horan SJ, Horan MP, Mohale NG, Recovery and re-use of domestic wastewaters using	2009	Using algal biocatalysts – the entire Flamongo series of publications are informative.	Only sees algae as biomass for further use, needs more work to investigate commodity chemicals.

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		integrated ponding systems: A key strategy in sustainable sanitation. Flamingo series no 13			
B BNR	148	1537/1/09: du Toit GJG, Parco V, Ramphao M, Wentzel MC, Lakay MT, Mafungwa H, Ekama GA, To investigate the performance and kinetics of biological nitrogen and phosphorus removal with ultrafiltration membranes for solid-liquid separation	2009	Aim 1: Evaluate biological nutrient removal (BNR) performance at typical membrane bioreactor (MBR) total suspended solids (TSS) concentrations (14-18 g/l). Aim 2: To compare the performance and kinetics of biological N and P removal under MBR conditions (high reactor TSS concentration (16 g/l)) with those in conventional BNR systems (low reactor TSS concentration (4 g/l)). Aim 4: Evaluate the impact of membrane solid liquid separation on the design of biological nutrient removal (BNR) activated sludge (AS) systems.	Adapt the findings to investigate the kinetics of bioproduction as well as nutrient removal in the wastewater context.
B BNR	149	1179/1/05: Cronje GL, Beeharry AO, Lakay MT, Wentzel MC, Ekama GA, Activity of heterotrophic and autotrophic biomass in BNR activated sludge.	2005	An investigation of the microorganism activity in biological nutrient removal, making wastewater biorefineries possible in principle.	More work required using this approach to determine activities of these organisms in a bioproduction context.
B BNR	150	692/1/02: Musvuto EV, Ubisi MF, Snyders M, Lakay MT, Wentzel MC, Treatment of wastewaters with high nutrient (N and P) but low organic (COD) contents.	2002	Treatment of wastewaters with high nutrient (N and P) but low organic (COD). This type of wastewater is often produced by primary forms of treatment (e.g. the supernatant of an AD), making this type of treatment especially relevant in terms of WWBR	The model developed needs to be experimentally tested over a wider range of water types, especially pH's, so as to be sure it applies in the context of a WWBR.
B BNR	151	137/1/86: Osborne DW, Lotter LH, Pitman AR, Nicholls HA, Enhancement of biological phosphate removal by altering process feed composition	1986	Biological phosphate removal	Useful in efficiently capturing phosphates in sewage. Could be applied in WWBR. Further work needs to be done on industrial wastewaters.
B BNR	152	TT 16/84: University of Cape Theory, design and operation of nutrient removal activated sludge processes	1984	The basis of biological nutrient removal, making wastewater biorefineries possible in principle	The model is limited in that it only considers nutrient removal and not recovery. The basis to maximize the maintenance coefficient of the microorganisms.
B DESAL	153	TT 266/06: du Plessis JA, Burger AJ, Swartz CD, Musee N, A desalination guide for South African municipal engineers.	2006	The purpose of this Guide is to: • provide a concise assessment of popular desalination technologies and related issues; • provide applicable guidance in the process of evaluating potential augmentation of municipal water supply through desalination, specifically within the context of available South African saline water sources. Such guidance is based on consideration of o saline water source quality and location,	Useful guide to inform WWBR considerations. Also helpful information in appendices. E.g. Appendix H: Membrane Technology companies (2006), Appendix I: Desalination plants in South Africa (owned by water supply authorities).

Category	Ref No	Authors & Title of Report	Year of publication	Value of research in context of wastewater biorefineries	Shortcoming of research in context of wastewater biorefineries / more work required
				o desalination technology and peripheral process selection, o operating and maintenance aspects, o environmental and socio-economic implications, o capital and operating cost estimates.	
B MEMBRANE		TT 636/15: Turner KN , Naidoo K, Theron JG , Broodry J , Investigation into the cost and operation of Southern African desalination and water reuse plants, Volume I: Overview of Desalination and Water Reuse	2015	water reuse and desalination process into context and provide an understanding of current state-of-theart treatment processes and configurations, including how these relate to the technology used at the identified plants	Study done on coastal regions. Not inland
B MEMBRANE		2006/1/14: Baker PGL; Richards HL; Phelane L; Iwuoha EI, The Development of Nano-Composite Polysulphone Membranes with Reduced Fouling Properties for use in Wastewater Treatment	2014	The use of hydrogels as ultrafiltration-type membranes, have been proven to be excellent coatings for PSF membranes due to their amphiphilic nature, biocompatibility and excellent resistance to non-specific protein and other macromolecules adhesion. This area of research is very new and could hold the key to developing an anti-fouling membrane for use in wastewater purification.	Improve membranes but scale up necessary to evaluate the membrane performance in a small scale membrane reactor using simulated separation mixtures as well as real organic membrane reactor feed solutions. . One of the drawbacks of using metal nanoparticles in environmental applications relates to potential environmental health-related issues as a result of metal nanoparticles leaching into the environment.
B MEMBRANE	154	2010/1/12: Garcin CJ, Harrison STL, Pilot Scale Treatment of Table Olive Brines	2012	The membrane was able to satisfactorily separate the high Mw phenolic components from the waste stream resulting in clear brine stream that was then sent to the chromatography system; this was able to produce a purified brine stream for recycle, whilst retaining the antioxidants for recovery. An average of 360 g of antioxidant product was produced per 1 kL batch of wastewater processed. The process is only feasible if there are value-added products to be obtained from a waste stream; if wastewater treatment alone is considered, it is expensive due to the high cost of the speciality membranes and the chromatography resin used.	Good case study to be incorporated into a WWBR scenario.
B MEMBRANE	155	1371/1/07: Edwards W, Leukes WD, Bezuidenhout CC, Riedel K-HJ, Vladimir Linkov M, Jansen van Rensburg PJ, Neomagus HWJP, Burgess JE, Dual-Stage Ceramic Membrane Bioreactors for the Treatment of High-Strength Industrial Wastewaters	2007	Membrane bioreactors for treatment of high strength industrial wastewaters while generating stable adapted microbial consortium. Stripped Gas Liquor (SGL) industrial effluent (COD of ± 2000 mg.L-1) was used.	Application to WWBR
B MEMBRANE	156	1374/1/07: Pillay VL, Jacobs EP, Development of a combined activated carbon/microfiltration	2007	Textile effluent was treated with combined activated carbon/microfiltration	Application to WWBR. Lab scale - needs scale up

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		process for the treatment of industrial effluents			
B MEMBRANE	157	1372/1/06: Lewis A, Nathoo J, Prevention of calcium sulphate crystallisation in water desalination plants using slurry precipitation and recycle reverse osmosis (SPARRO)	2006		Preventative maintenance, or WWBR including desalination units (utilizing the brines)
B MEMBRANE	158	1384/1/04: Marah I, O'Donovan M, Martin R, Boberg D, Evaluation of microfiltration, ultrafiltration and nanofiltration for salt and chromium recovery from spent pickling and tanning effluent	2004	Salt and chromium recovery from spent pickling and tanning effluent	
B MEMBRANE	159	1035/1/01: Domrose SE, Sanderson RD, Jacobs EP, Burch G, Cleaning and pre-treatment techniques for ultrafiltration membranes fouled by pulp and paper effluent	2001	foulant characterisation and foulant removal from UF membranes used in industrial effluent (paper and pulp) treatment under laboratory-scale conditions and pilot scale	As elevation of the pH of the effluent feed to the UF plant reduced the rate and degree ofmembrane fouling considerably.
B MEMBRANE	160	847/1/98: Domrose SE, Finch DA, Sanderson RD, Development of transverse-flow capillary-membrane modules of the modular and block types for liquid separation and bioreactors	1998	Development of cost effective membrane cartridge modules of up to 10m2, multi-cartridge modules of up to 100m2, manifolding for capillary membrane modules and transverse flow capillary membrane module	Design optimisation
B MEMBRANE	161	548/1/97: Jacobs EP, Barnard JP, Investigation to upgrade secondary treated sewage effluent by means of ultrafiltration and nanofiltration for municipal and industrial use	1997	The objectives of the research were to determine to what extent medium-molecular-mass cut-off capillary ultrafiltration and tubular nanofiltration membranes, could be used to improve the quality of secondary treated sewage and water, over extended operating periods.	Membrane filtration is likely to be a useful technology for WWBRs, and the work presented in this report may inform operating and design decisions regaring membrane operating times.
B MEMBRANE	162	362/1/95: Malherbe GF, Morkel CE, Bezuidenhout D, Jacobs EP, Hurndall MJ, Sanderson RD, Industrial applications of membranes	1995	laboratory evaluation of various experimental membranes made at the Institute for Polymer Science (IPS) and made available in development quantities for use on real or simulated effluents, including evaluation at industrial sites. BRACKWATER TREATMENT, SASOL COOLING-WATER	Use in WWBR

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				BLOWDOWN, POTASSIUM BITARTRATE REMOVAL FROM WINE RESTS, SEAWATER PRETREATMENT FOR RO DESALINATION	
B MEMBRANE	163	242/1/90: Bailey AD, Dold PL, An exploratory investigation of crossflow microfiltration for solid/liquid separation in biological waste-water treatment	1990	exploratory investigation into the application of Crossflow Microfi1tration (CFMF) for solid/liquid separation in two biological wastewater treatment systems. The systems chosen were the Upflow Anaerobic Sludge Bed (UASB) reactor and the aerobic Activated Sludge systems.	operating conditions
B MEMBRANE	164	337/1/90: Strohwald NKH, Removal of algae from water by ultrafiltration	1990	(drinking water section – low concentrations?)	Feasible as DSP?
B NANO	165	KV 195/07: Schutte CF, Focke WW, Evaluation of Nanotechnology for application in water and wastewater treatment and related aspects in South Africa.	2007	Three general areas have been identified: (i) water treatment technology including development of improved membranes and development of activated filter media, (ii) development of real-time diagnostic tools for water quality assessment, (iii) development of membrane-based wastewater treatment technology. These may have application in WWBR.	Nanotechnology is a broad term, which is of limited usefulness. Some specific applications however may be useful, but these need to be evaluated on a case-by-case basis.
B SOLIDS	166	333/1/97: Whyte DC, Swartz CD, The removal of suspended solids from pulp and paper effluents by employing the combined sedimentation flotation process	1997	Suspended solids in the effluent of pulp and paper mills are comprised of both less dense particles (mainly fibres) and denser particles such as clay. this project investigated, at pilot scale, the use of a compact inclined plate settler integrated ahead of a flotation cell. The advantage of this configuration is the high rate of sedimentation coupled to the shorter solids retention time within the unit. The most significant conclusions of this study are that high percentages of removal for suspended solids can be obtained with the combined SEDIDAF process; the settling stage of the process contributes most to the overall removal of solids from the effluent; effective suspended solids removal can be obtained with settling in an inclined plate settler at surface loading rates as high as 10.9 m/h; improved suspended solids removal is obtained at lower flotation zone velocities in the DAF stage; the DAF stage does not only remove the organic fraction of the suspended solids but also inorganic particles; and, the settling stage does not only remove the inorganic fraction of the suspended solids, but also organic particles.	Investigate the application potential for WWBR. Has this been applied to industry since publication of this report?
B SSF	167	766/1/05: De Jesus AE, Heinze PH, Muller JR, Nortje GL, Utilisation of earthworms and associated systems for the	2005	A typical D-Grade abattoir (that slaughters up to 15 head of cattle per day) generates up to 1 ton of wet rumen contents and blood and up to 34.7 kl total wastewater per day. An important benefit of vermicomposting is that processing can take place in situ and that worthless or decomposing wastes need not be transported over long	Investigate the use of vermicompost or vermiculture for pre-treatment of biosolids before the Biosolids reactor, including further research aspects as highlighted in the report.. Investigate potential higher-value products from vermiculture. Lower value products include fertiliser, compost, potting soil, protein.

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		treatment of effluent from red meat abattoirs.		distances. The end products have value as fertilizer, compost, potting soil and as a protein source. The purpose of the current project was to "clean up" wastewater in addition to solid wastes. It differs from the standard vermicomposting process in that large volumes of wastewater pass through the system. The main problem that had to be solved was to ensure that the earthworms remained sufficiently active to convert the solid effluent to vermieompost under conditions where large volumes of liquid effluent passed through the system. A single container, adapted to ensure better filtration and harvesting of the vermicompost was designed and a laboratory-scale prototype built and evaluated. The earthworm ecosystem could be adapted to tolerate addition of blood provided it was not too concentrated (blood 0,7 % of the feed liquid). Provided the water could drain away within hours (about 3 hours in the present series of experiments), the earthworms were able to maintain a good speed of composting (10-15 cm per week) even when large volumes of water (similar to the amount of effluent from an abattoir) passed through the system. The system works well provided the layer of added solids does not exceed 2-3 cm per day; the liquid drains away fairly fast and aerobic conditions are maintained. The present process opens up the possibility to rid abattoir effluent of solids and to make the resultant liquid effluent more amenable to further treatment with existing systems. The effluent from the earthworm plant is not yet sufficiently clean to be released into the environment without further cleaning and polishing.	
B SSF	168	1129/1/04: Burton SG, Ryan DR, van Wyk L, Bioreactor systems using the white rot fungus Trametes for bioremediation of industrial wastewater	2004	Development of a practicable bioremediation process for using the enzymes of Trametes versicolor to degrade pollutants in specific industrial wastes, namely chlorinated aromatics and phenolics produced by the pulp-and-paper and petrochemical industry. Large scale, cost-effective applications of white-rot fungi to continuous treatment of liquid effluent has previously been hindered by the lack of suitable bioreactor systems. A hollow fibre membrane bioreactor and a trickle filter were investigated for suitability as supports for immobilised biofilms of T. versicolor and laccase production and pollutant degradation were successfully demonstrated in both reactor configurations. However, the need for a simple, cost effective, yet simple to upscale reactor system led to the investigation and development of an airlift loop reactor (ALR). Increased growth (10g/L dry mass) and enzyme production (12000U/L) as well as highly efficient effluent degradation (5% v/v/day) were achieved in the ALR	Investigate the value of this work in context of WWBR - does it optimise well as a unit process in the treatment strain? Take the system to larger scale and demonstrate its effectiveness at pilot scale.

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				in fermentations over two week periods. Immobilised biofilm reactors in the form of a Transverse Flow Membrane Bioreactor and a Trickle Bed Reactor were identified as suitable for growth, enzyme production and phenolic removal by T. versicolor.	
B SSF	169	331/1/01: Pretorius WA, Willie P, Oxygen transfer in filamentous biocultures	2001	In wastewater treatment, Chemical Oxygen Demand (COD) balances are used to determine the oxygen requirement of a particular biological wastewater treatment process. This same method, although very cumbersome, could be used to determine the oxygen transfer efficiency in a biological growth system. This was the method used in this study to determine the aeration efficiency under various experimental conditions.	Fairly fundamental work on aeration. May have WWBR application, specifically in biosolids reactor studies.
B SSF	170	535/1/98: van der Westhuizen TH, Pretorius WA, Use of filamentous fungi for the purification of industrial effluents	1998	This is a report on an investigation conducted to determine the potential of using the micro-screen process to convert industrial effluent COD into biomass that can be used for secondary purposes. The report describes the development of the process on one specific effluent, but the process is equally suitable for a large range of effluents in many of the organic industries world-wide. The effluent under discussion in this report is a typical low acetic acid containing effluent, but it also contains inhibiting substances that made conventional biological treatment difficult. Notes: Bacterial contamination above a certain degree influences the dewatering characteristics and product quality of the biomass. Two possibilities for commercial use of the biomass have been investigated, namely use of the dried biomass as protein source, and secondary batch fermentation of the harvested biomass to produce celluiase enzymes.	Liquid fungal culture application. The approach to challenges are useful for WWBR approaches, specifically since the process relies on dynamic selection principles to sustain the filamentous culture, any possible bacterial contamination had to be quantified.
B UASB	171	1248/1/06: Foxon KM; Buckley CA, Brouckaert CJ, Dama P, Mtembu DZ, Rodda N, Smith M, Pillay S, Arjun N, Lalbahadur T, Bux F, The evaluation of the anaerobic baffled reactor for sanitation in dense peri-urban settlements.(ABR)	2006	Technology that may be relevant for WWBR: The evaluation of the anaerobic baffled reactor for sanitation in dense peri-urban settlements.	Possible application to WWBR in dense peri-urban settlements, as a model of decentralised production.
B UASB	172	1364/1/06: Sigge GO, Britz TJ, McLachlan T, van Schalkwyk N,	2006	Lab scale experiments and scaled up to 600 L. Good report for WWBR.	

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		Treatment of apple and wine processing wastewaters using combined UASB technology and ozonation scenarios.			
B WETLAND	173	TT 438/09: Kotze DC, ASSESSING THE SUSTAINABILITY OF WETLAND USE	2009	A model developed to assist in assessing the ecological sustainability of wetland use, focusing on grazing of wetlands by livestock, cultivation of wetlands and harvesting of wetland plants for crafts and thatching.	Limited direct applicability to WWBRs, but could potentially be adapted to be applied to macrophyte operations.
B4 MEMBRANE	174	TT 556/12: Edwards W, Marshall Sheerene Sheldon MS, Zeelie PJ, De Jagers D, Dekker LG, Bezuidenhout CC, Water Reuse for Industrial Wastewater	2013	Performance of dual-stage Membrane BioReactor (MBR) for the treatment of textile and paper mill effluent, including economic viability assessment.	Technology applicable to WWBRs, already demonstrated on several wastewaters.
B4 MEMBRANE	175	2011/1/13: Tandlich R, Luyt C, Tyalana K, Moyo F, Application of emulsion liquid membranes in the extraction of rhodium from mining and metal refinery effluent	2013	This project set out to investigate the application of emulsion liquid membranes (ELMs) in recovering platinum group metals (PGMs) from the aqueous by-products of PGM refining. Extraction of Rh from aqueous matrices was tested and the results showed that the complete extraction of Rh was possible. This was achieved by the use of an optimised ELM. Carryover of the diluent components into the stripping phase and effluent was observed and further work is recommended to overcome this drawback.	A possible route to extract metals from wastewaters either as part of a WWBR process train or as a pre-treatment step to make the water more suitable for bioconversion.
B5 WETLAND		2104/1/14; Welz PJ, Ramond J-B, Cowan DA, Smith I, Palmer Z, Haldenwang R, Burton S, Le Roes-Hill M, Treatment of winery wastewater in unplanted constructed wetlands		Expanded on the knowledge generated from their previous WRC-funded project (K5/1936) to understand how constructed wetlands may be adapted for "real world applications"	By definition, constructed wetlands contain plants. This strict definition is debateable because many natural wetlands do not contain plants. Nevertheless, to avoid confusion, the systems used in the project are referred to as biological sand filters.
B6 NANO	176	1991/1/13: Pletschke B, Torto N, Frost C, Zeni Tshentu Z, Electrospun nanofibre-based strategies for removal and detection of water contaminants	2013	electrospun nanofibre-based devices for water purification as well as monitoring of water quality.	DSP for WWBR. Also for process analysis.
B6 NANO	177	1897/1/12: Leslie Petrik L, Ndungu P, Nanotechnology in water treatment	2012	removal of several inorganic and selected organic contaminants such as acid rock drainage (ARD) from various mines in the Gauteng and Mpumalanga regions, industrial brine effluents, dyes, and bacterial laden water	Technology that can be used in WWBR

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C	178	Biomimicry for Constructed Wetlands: Looking To Nature For Solutions On Water Treatment	2013	WRC project is ongoing. Biomimicry is a good design tool to facilitate systems thinking, and shares the holistic approach of wastewater biorefineries.	Data is lacking, this is not a robust engineering application. This may improve as this project progresses.
C	179	TT 565/13: Swartz CD, vd Merve-Botha M, Freese SD, Energy Efficiency in the South African Water Industry: A Compendium of Best Practices and Case Studies	2013	A stepping stone towards biorefineries using the cleaner production approach	Focused on energy reduction. More work required on on-site energy production and integrated unit operation, e.g. waste-heat recovery
C	180	KV 323/13: van Vuuren SJ, Loots I, van Dijk M, Barta B, Energy Generation using Low Head Technologies	2013	The results of investigation indicate clearly that there are significant potential for the development of low-head hydropower in ... wastewater treatment infrastructure. It is significant on the background of the potential reduction in electricity demand on the national grid presently supplying the conveyance, pumping and treatment of raw water and the treatment of large quantities of urban wastewater.	Co-generation may be of relevance to WWBR. It needs to be determined how the low head hydro technology will impact plant operation.
C	181	TT 546/12: Mvuma GG, Hooijman F, Brent AC, Oelofse SHH, Rogers DEC, Volume III: Development and assessment of technological interventions for cleaner production at the scale of the complex	2012	Key factors that influence the environmental sustainability of a large inland industrial complex: The Secunda Industrial Complex.	Assessment of cleaner production options and environmental assessment by LCA
C	182	TT 485/11: Barclay S, Trusler G, von Blottnitz H, Buckley CA, Kothuis B, Janisch C, Cleaner Production: A Guidance Document for the Mining Industry in South Africa	2011	Helping to implement cleaner production in mining industry	The use of cleaner production tools such as quick scan assessments, life cycle assessments, and cleaner production forums to encourage and motivate the mining industry to implement cleaner production in order to reduce their environmental impact and increase profitability
C	183	1553/1/11: Trusler G, Mzoboshe S, The introduction of cleaner production technologies in the South African mining industry: a summary report	2011	Cleaner production technologies describes a preventative environmental approach, aimed at increasing resource efficiency and reducing the generation of waste at source, rather than addressing and mitigating just the symptoms by technically treating an existing waste or pollution problem	Good guidelines for general approach in WWBR.
C	184	1898/1/11: Majozi T, Adekola O, Water Use Optimization in industry: A Mathematical Model for a Multipurpose Batch Plant	2011	It is desirable to minimize the production of pharmaceutical effluent at worst and eliminate it at best. This report presents a methodology to address the problem of wastewater minimization, over longer time horizons, including by extending the concept of water reuse to include a regeneration system. This study systematically presents	Can this model be applied to running WWBR efficiently? Probably of little relevance.

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				mathematical formulations and detailed case studies where these techniques have been applied with freshwater savings in excess of 25%.	
C	185	1542/1/08: Mbolekwa Z, Buckley CA The removal of reactive dyes from dye liquor for the reuse of salt, water and energy	2008	The aim of the project was toš establish the process parameters governing the recovery of water and chemicals for reuse from reactive dye baths using activated carbon.	Further research in this area should concentrate on evaluating different activated carbons and role of auxiliaries in activated carbon adsorption studies. This study proved that the activated carbon adsorption technique is the solution in reactive dyeing textile industries because of the possibility for re-use of water, salt and energy; thus enabling environmental improvements with savings in salt, energy and water.
C	186	1625/1/08: Majozi T, Gouws JF, Development of a complete process integration framework for wastewater minimisation in multipurpose batch plants.	2008	Development of a mathematical optimisation technique for wastewater minimisation, speicifcally in batch systems, that could be applied to industrial scales.	This technique could prove to be invaluable for WWBR reactor scheduling and optimisation.
C	187	1673/1/08: Mazema HK, Ally SH, Kamish W, Muhaydien A, A pilot study into available upstream cleaner production technologies for the petroleum refining industry to meet the requirements of the waste discharge charge system.	2008	Provides an assessment of the Cleaner Production technologies available to the petroleum refining industry, and the waste discharge charge system (WDCS) based on the available cleaner production initiatives.	NB for WWBR on site for petroleum industry
C	188	TT 283 & 4/07: Barclay S, Buckley C, Waste minimisation clubs in South Africa (Facilitation and Training Manual)	2007	Cleaner production initiative	
C	189	1368/1/07: Fraser D, Ndwandwe K, Basnal P,Isafiade A, Nyathi NS, Majozi T, Brouckaert CJ, Brouckaert BM, Water conservation through energy conservation.	2007	Reducing water usage through efficient energy, heat and water use.	Focused on heat exchanger networks for reduced energy consumption, and a similar method for water use reduction. More work required on on-site operation, e.g. waste-heat recovery.
C	190	1266/1/06: Grove B, Whole-farm model to optimise water use.	2006	Stochastic modelling of water usage on farms.	Package plants most often fail in their ability to effectively nitrify ammonia and in disinfecting against bacteria, due to faults in design and operation, not due to the process technology per se. More work required to evaluate the suitability of these package plants for

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					modular use in wastewater biorefineries in communities. - link up with SEWPACKSA?
C	191	TT 139/00: Barclay S, Buckley C, Waste minimisation guide for the textile industry: A step towards cleaner production. Vol I. (and TT 140/01 and TT 161/05)	2000	Minimising wastewater in textile industry	Development of flowsheets for minimising water and energy usage in the textile industry; Assessment and categorising of waste streams; Aim is to reduce environmental impact and comply with legislations
D		2131/1/15: Tesfamariam EH; Annandale JG; de Jager PC; Ogbazghi Z; Malobane ME; Mbetse CKA, Quantifying the fertilizer value of wastewater sludges for Agriculture	2015	To develop a user friendly sludge application rate advisor computer model that takes into account both the fertilizer value of sludge and crop nutrient requirements	Further analyses required i.t.o. effect of post wastewater treatment dewatering techniques on fertilizer value
D	192	KV 320/13: van Niekerk A, Schneider B, Implementation Plan for Direct and Indirect Water Re-use for Domestic Purposes-Sector Discussion Document	2013	focused specifically on the direct and indirect reuse of domestic treated wastewater as a proactive step to generate a sector discussion document for the progressive implementation of the Water Re-use Strategy. The project developed a plan to bridge the gap between the strategy and implementation of water re-use for domestic water use in consultation with the Department of Water Affairs.	Possible opportunities for WWBR ito Developing appropriate technologies and undertaking baseline studies to determine the status of indirect / direct domestic / potable water re-use
D	193	1724/1/12: Tesfamariam EH, Annandale JG, de Jager PC, Mbakwe I, van der Merwe P, Nobela L, van der Laan M, Sustainable Agricultural Use of Municipal Wastewater Sludge, 1724/2/12: The potential of sludge amended combustion coal ash residues	2012	An investigation of use of sludge (both municipal waste derived, and petro-chemical waste derived) for agriculture.	Recovery and re-use of N and P out of sludges for agriculture. More work required on the stages of processing that still considers the product (more than just soil additive) as originating from sludge.
D	194	TT 520/12: Fessehazion KM, Abraha AB, Everson CS, Truter WF, Annandale JG, Moodley M, Water use and nitrogen application for irrigation management of pasture production	2012	Water use and nitrogen application for irrigation management of pasture production	Water from WWBR could be used in pasture irrigation – this study informs that. However, limited applicability to WWBRs.
D	195	1937/1/11: Burton SG, Mupure CH, Horne KA, Jones S and Welz	2011	Beneficiation of Agri-Industry Effluents	Downstream processing of agri-wastes, for recovery of valuable products (phenols, antioxidants and sugars). A closer evaluation of

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		PJ, Beneficiation of Agri-Industry Effluents			the (economic) feasibility and market potential of concepts highlighted in this study.
D	196	1937/1/11: Burton SG, Mupure GH, Horne KA, Jones S, Welz PJ, Beneficiation of Agri-Industry Effluents	2011	The feasibility of wastewater beneficiation depends largely on the concentrations of valuable by-products present and the efficiency of the extraction processes that can be applied. The paper reviews apple and citrus wastewaters were analyzed.	Very early level research, possibly not considering economically viable, bulk commodity products that is expected to be more suitable for WWBR application.
D	197	TT 351/09: Herselman JE, Burger LW, Moodley P, Guidelines for the Utilisation and disposal of wastewater sludge, Volume 5, Requirements for thermal sludge management practices and for commercial products containing sludge.	2009	Report series aims to provide options and opportunities for WW sludge use innovation. Where wastewater sludge cannot be used as a resource, the guidelines also provide for its disposal in a responsible manner.	The guidelines will likely apply to the operation and products from WWBRs, however these guidelines will likely require further clarification and adjustment.
D	198	KV 187/07: Burton SG, Garcin CR, Aucamp JH, Beneficiation of wastewaters from the South African citrus industry- A feasibility study	2007	Examines two principal products (an oil and a carbohydrate) from citrus wastewaters, with preliminary technoeconomic evaluation.	Good applicability to WWBRs, giving a techno-economic assessment of a wastewater to products example.
D	199	1242/1/05: Petrik L, White R, M; Somerset V; Key D; Iwuoha E; Burgers C; Fey MV, Klink Utilization of fly ash for acid mine drainage remediation	2005	This report details the use of fly ash, from coal fired power, to treat acid rock drainage, and producing zeolite from the resultant product. This technique disposes of two hazardous materials, and produces a saleable product simultaneously.	This technique could prove useful in WWBRs if ARD is to be treated, and if fly ash is available. However, more work is required on the scale-up and techno-economic evaluation of the method.
D	200	1367/1/05: Christopher L, Bio-remediation and Bio-utilization of pulping and bleaching wastewaters.	2005	This technical paper demonstrates the reduction of toxic chemical use when using alternative bleaches, such as enzymtatic approaches. Furthermore, valuable products (such as the abovementioned enzymes) can be produced from the pulp wastewaters.	The application of the wastewater technology (cleaning pulp wastewater to produce enzymes) is applicable to WWBRs, while not the first part of the report.
D	201	1210/1/04: Snyman HG, van der Waals JH, Laboratory and field scale evaluation of agricultural use of sewage sludge.	2004	An investigation of use of sewage sludge in agricultural soil amendment, including composition and characteristics, and the potential for accumulation of heavy metals and pathogens.	potentially applicable to WWBRs, as sludge for agricultural soil amendment may be a valuable product. However, furth work on WWBR sludges in the same space are needed.
D	202	366/1/94: Loots PA, Oellermann RA, Pearce K, Pilot studies on phosphate crystallization in biological wastewater treatment systems	1994	Phosphate recovery using crystallization in biological wastewater treatment systems	Steady state was not achieved at the pilot scale and thus the study did not achieve the objective of full scale testing due to process instabilities. Potential to investigate work again if more detailed thermodynamic data relating to phosphate crystallization can be found.

Category	Ref No	Authors & Title of Report	Year of publication	Value of research in context of wastewater biorefineries	Shortcoming of research in context of wastewater biorefineries / more work required
D AGRIC	203	TT 430/09: Stimie CM, de Lange M, Crosby CT, Erna Kruger E, Agricultural water use in homestead gardening systems	2009	To improve food security through homestead gardening, by developing and evaluating the appropriateness and acceptability of training material for water use management, training the trainers and training of household members in selected areas.	Some systematic thinking about disperse small scale processes could be applicable to regional WWBRs, however, mostly inapplicable.
E	204	2012/1/13: Randall D, Lewis A, Rodriguez-Pascual M, Nathoo J, Reddy T, Apsey G, Kapembwa M, Egan T, Chivavava J, Extended Investigations into Recovery of Water and Salts from Multi- component Hypersaline Brines using Eutectic Freeze Crystallization	2013	Recovery of water and salts from industrial (coal and platinum mining) wastewaters. This could be implemented in WWBR if a brine stream is part of the process.	This work needs to be extended to other complex brines, from other industrial sources. Application in WWBR to be shown.
E	205	2013/04/12; Dunn K; Rose P; Arthrospira (Spirulina) in tannery wastewaters. Part 1: The microbial ecology of tannery waste stabilisation ponds and the management of noxious odour emissions using microalgal capping Part 2: Evaluation of tannery wastewater as production media for the mass culture of Arthrospira biomass.	2013	(Spirulina) in tannery wastewaters. Part 1: The microbial ecology of tannery waste stabilisation ponds and the management of noxious odour emissions using microalgal capping Part 2: Evaluation of tannery wastewater as production media for the mass culture of Arthrospira biomass.	Possible application to WWBR, a case specific application
E	206	1543/1/10: Mapolie SF, Saptarshi, Darkwa J, Van Wyk JL,Industrial wastewater remediation via wet air oxidation using immobilised transition metal catalysts	2010	Using catalytic wet air oxidation for removing organic materials from industrial effluents. Using phenol as model chemical to be removed	Evaluation of suitable reactor systems for the catalytic processes.
E	207	1363/1/08: Binda M, Gounder P, Buckley CA, Barbara, Promotion of biodegradable chemicals in the textile industry	2008	Development of score system for tectile industry effluent. A pilot studt of implementing the score system at volunteer factories.	This methodology could be usefully applied to WWBRs, for influent and effluent analysis. However, more work is required to apply the methodology to other indutrial effluents.
E	208	1546/1/07: Petrik LF, Hendricks NR, Ellendt AAM, Burgers CL, Toxic element removal from water using zeolite adsorbents made from solid waste residues	2007	Preliminary study on the use of fly ash to neutralise acid rock drainage, and the subsequent production of zeolite adsorbant materials from the residue of this process for toxin removal from wastewaters.	Limited applicability to WWBRs, although toxin removal from WWs may be important in WWBRs.

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E	209	1377/1/05: Taljaard L, Venter A, Gorton D, An evaluation of different commercial microbial or microbially-derived products for the treatment of organic waste in pit latrines.	2005	Pit latrines operate on the principle of anaerobic decomposition. This process, however, is very slow, leading to organic waste build-up and subsequent system blockages. There are claims that the use of microbial or microbially-derived products for the treatment of organic waste in pit latrines controls odour and also reduces the bulk of the organic material. A total of 16 products were obtained. There were minimal changes in the pits treated with Product M and no changes in the control pits. The odour and the population of flies in the treated latrines (especially with Product B) disappeared after the first dosages, whereas bad odours and Hies persisted in the untreated latrines.	More work required to evaluate if these bioproducts can be produced from wastewater, as well as their efficacy in situ. Future work could include a biological study into the claimed mode of action of these biological products. The products should be evaluated on the basis of the amount and type of microorganisms and enzymes present, and compared to the information and claims on the specification sheets.
E	210	1072/1/05: Neomagus HWJP, Bio-polymeric heavy metal adsorbing materials for industrial wastewater treatment.	2005	The removal and recovery of heavy metals using the biosorbent chitosan is investigated. Since flakes do not have good adsorption characteristics and are difficult to use in large equipment, other configurations (beads, membranes and immobilised chitosan) were prepared for the experimental adsorption studies. The adsorption experiments were carried out at a laboratory scale. A gel type of material was formed, containing predominantly water (93-96%) and the balance chitosan (4 – 7%). For the chitosan beads, a novel adsorption model has been developed, which takes the acid base characteristics of the chitosan into account. The new model can therefore be used at any pH, for both adsorption and desorption. From this model, it could be concluded that the chitosan has the largest affinity to copper, followed by lead, nickel, zinc and cadmium.	Investigate the possibility of recovering chitosan from (fisheries?) wastes in a WWBR systems-thinking setup (even just a paper based study), explore where co-siting of metal recovery may be an option. Explore chitosan-related thinking in a dilute context: this study focused heavily on increasing concentration and throughput, which affects chitosan stability and costs. Market potential: "Since chitosan is only produced at a small scale, the prices on the world market are relatively high ($ 35/kg). Since the market for chitosan is rapidly growing (mainly for the application of fat absorber), price decreases are expected in the future."
E	211	1259/1/05: Petersen F, Aldrich C, Esau A; Qi BC, Biosorption of heavy metals from aqueous solutions.	2005	The project's objective was to investigate the feasibility of using biomaterials for the removal of heavy metals from aqueous effluents by first identifying a suitable biosorbent, characterizing the sorbent and evaluating its use on an industrial scale.	WWBRs will likely need to be able to treat wastewaters containing heavy metals, and so this technology could prove useful for their removal. However, further work on the limitations and applications of the technology is needed.
E	212	1170/1/04: Whiteley CG, Pletschke BI, Burgess JE, Tshivhunge AS, Ngesi N, Whittington-Jones K, Enongene G, van Jaarsveld F, Heron P, Rashamuse, Rose PD, Investigation into the enzymology of accelerated primary sewage sludge solubilisation and digestion in sulphate reducing systems.	2004	A study of a bioproduct (enzyme) to be used in sulphate reducing systems. This study has indicated that the enhanced mineralisation of complex particulate organic matter in sewage sludges relies primarily on enzymatic hydrolysis of the micromolecules. Furthermore it provides a view of the enzymology of the RSBR with respect to depth of the reactor and concomitant effect of levels of sulphide, sulphate and alkalinity/pH of the overall system.	More work required to evaluate if these enzymes can be produced as marketable and financially viable bioproducts from wastewater.

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E	213	723/1/04: Summers GF, Designed functionalized polymers by anionic macromolecular engineering for membrane development and fabrication.	2004		Bio application. Could be produced by WWBR (biologically or physic-chem)
E	214	1040/1/03: Graz CJM, Stilwell KM, McComb DG, A two-enzyme cleaning-in-place programme for South African dairies	2003	Production on enzymes (bioproduct) in a cleaning programme in SA dairies	To produce an economically viable biological cleaning system for dairy plants. To screen microbes isolated on-site in a dairy for their extracellular enzymes which can degrade milk constituents. Can this enzyme be used/produced in WWBR.
E	215	1083/1/02: Swalaha FM, Datadin S, Choonawala BB, Assessment and application of imported biomass for the bioremediation of heavy metal effluents	2002	Bioremediation	Assessing treatment options for metals contaminated waste streams from metal mining and metal processing facilities
E	216	932/1/02: Leukes W, Edwards W, Buchanan K, Bezuidenhoudt J, Jordaan J, Watcham C, Way-Jones N, Enzymatic defouling of ultrafiltration membranes: A defouling-on-demand strategy using immobilised enzymes	2002	Enzymatic cleaning has been offered as an alternative to chemical cleaning since enzymes are biodegradable and do not cause additional pollution problems. Enzymes are immobilised onto the ultrafiltration unit	Produced from WWBR. large-scale, low-cost production of the thermostable laccase should be developed for provision of sufficient enzyme for pilot-scale testing. Also, effective process design needs to be done to formulate this technology into a usable operating system.
E	217	623/1/96: Talbot MMB, Ascough SW, Rankin A, Bio-enhancement of a river system using a biological catalyst	1996	Bio-enhancement of a river system using a biological catalyst	If effective, can this biocatalyst be produced in WWBR?
E	218	531/1/96: Swart P, Maartens A, Engelbrecht J; Allie Z, Jacobs EP, The deveolpment of characteristics and cleaning techniques to classify foulants and remove them from ultra- and microfiltration membranes by biochemical means	1995	The deveolpment of characteristics and cleaning techniques to classify foulants and remove them from ultra- and microfiltration membranes by biochemical means. There are a number of commercial enzyme preparations available on the market that are used for cleaning purposes in the food industry These preparations are not specific and a broad spectrum of biological materials will be removed by them In membrane installations where fouling can be attributed to one or more main group(s) of biological molecules, the development of specialised enzyme systems, highly specific for particular fouling agents, will be the most cost and time effective method for the removal of foulants from the membrane surface.	Bio application. Could be produced by WWBR (biologically or physic-chem)
E	219	318/1/94: Cloete TE; Brözel VS; de Bruyn EE; Pietersen B,	1994	Recent studies have indicated that biofilm ecosystems respond to stress (i.e. biocides) in ways similar to macro-ecosystems. Generally,	Limited application to WWBR. Knowledge may be useful for optima process control in units.

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		Optimisation of biofouling control in industrial water systems		there is a decline in species diversity and a selection of more tolerant isolates. Mucoid mutants did not exhibit increased tolerance to bactericides, indicating that extracellular polysaccharide does not confer increased resistance to bacteria in biofilms. Attached cells were more resistant than free-living cells within 15 min following attachment. Cell age had a marked influence on resistance, where actively growing cells were most resistant and late stationary phase cells were least resistant.	
E	220	1165/1/06: Jacobs EP, Swart P, Bredenkamp MW, Allie Z, Govender S, Liebenberg L, van Kralingen L, Williams WT, Development of technology for the selective removal of bioactive pollutants by ligands, non-covalently immobilised on membranes.	2006	The development of a technique by which biologically active species, specifically endocrine disruptive chemicals, could be separated from water by way of selective ligands immobilised on membranes.	Technology applicable to WWBRs, especially if potable water is to be produced from wastewaters which may contain EDCs. However, this technology requires further development and scale-up.
F		1822/1/14, Ikumi DS, Harding TH, Vogts M, Lakay MT, Mafungwa H, Brouckaert CJ, Ekama GA, Mass balances modelling over wastewater treatment plants III	2015	To develop three phase (aqueous-gas-solid) steady state and dynamic mathematical models for the anaerobic and aerobic digestion of sludge; including waste activated sludge (WAS) produced by enhanced biological phosphorus removal (EBPR) plants, within a plant-wide setting.	No standardardisation in modelling software. Frustration between consultants and munciple users
F	221	TT 601/14: Environmentally Sustainable Beneficiation of Brewery Effluent: Algal ponding, Constructed Wetland, Hydroponic Vegetables and Aquaculture Clifford LW Jones, Peter J Britz, Rory Scheepers, Sean Power, Anneke Cilliers & Richard Laubscher Report to the Water Research Commission by Department of Ichthyology and Fisheries Science, Rhodes University WRC Report No TT 601/14	2014	This project aimed to develop a sequence of effluent treatment methods using existing technologies, such as algal ponding and constructed wetlands, to develop a unique, low cost, low-tech, environmentally sustainable industrial water treatment process. It also aimed to combine these technologies with the production of algae, vegetables and fish in such a way that the end result was not only treated industrial effluent, but also the production of recovered water available for reuse and/or used for producing valuable downstream products. The project's goal was to take industrial effluent and, using little more than the sun's energy and photosynthesis, turn it into clean water, valuable algae, fresh vegetables and fish (swordtail (Xiphophorus helleri) - classified as a nuisance pest though, so not suitable).	Has details of people who may be useful to guide WWBR further included in report (page xv). Is there a techno-eceonomic analysis done on this work? Would it be able to scale to other WWBR applications? From the report: In the initial baseline studies it was demonstrated that the high rate algal pond/wetland system was a viable alternative to an activated sludge system, with a substantially lower environmental impact and lower operating costs than the more conventional method of treating effluent. The geographic footprint (i.e. the space) required to operate a full-scale high rate algal pond or constructed wetland system would be substantial, so optimising its performance was identified as a priority. The research that followed was thus aimed at increasing the flow of effluent through the systems without compromising the efficiency of nutrient removal, thus determining the minimum size of the physical footprint required to treat a given volume of effluent. In autumn it was possible to reduce the hydraulic retention time of the HRAP from 18.6 d to 3.8 d, and in summer to 2.5 d. The drop in pH (9.0 to 8.5) and ammonia (6 to 2

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					mg/L) levelled off within 13 m of the linear wetland. Further work was required to (a) refine the required length of constructed wetland and (b) determine seasonal variation in the required hydraulic retention time in the constructed wetland.
F	222	TT 587-14: Verster B, Madonsela Z, Minnaar S, Cohen, Harrison STL, Introducing the wastewater biorefinery concept	2014	Introducing the biorefinery concept specifically – the precursor to this current project.	As an introduction, this study still lacks scope and depth of opportunities and risks (partially adressed in this current report)
F	223	1803/1/13: Blignaut J, de Wit M, Milton S, Esler K, le Maitre D, Mitchell S, Crookes D, A market for ecosystem goods and services following the restoration of natural capital: Volume 1: Main Report (and 1803/2/13)	2013	Integrated system dynamics model on the likely impact of restoration on the ecology, hydrology and economy of restoration sites	Ecosystem economics possibly applicable to WWBR, although products are not the focus of the model.
F	224	TT 399/09: Burton SG, Cohen B, Harrison S, Pather-Elias S, Stafford W, van Hille R, von Blottnitz H, Energy From Wastewater – A Feasibility Study (Essence Report)	2009	An overview of the chemical potential of wastewater, making wastewater biorefineries possible in principle	Only considers energy product, more work required for commodity chemicals, and Nitrogen and Phosphate containing product
F	225	1541/1/08: Mutambanengwe C, Oyekola O, Togo C, Whiteley CG, Production of Enzymes for Industrial Wastewater Treatment – Proof of Concept and application to the textile dye industry.	2008	Based on work on the BIOSURE process, this study undertook a thorough investigation to show that hydrogenase enzymes, also found within the biosulphidogenic reactor, could be used to bioremediate industrial waste effluent from the textile dye industry.	A good example of producing enzymes from wastewater via the BIOSURE process - possible case study of WWBR.
F	226	TT 235/04: Rouhani QA, Britz PJ, Contribution of aquaculture to rural livelihoods in South Africa: A baseline study	2004	Aquaculture is the beneficial and sustainable use of water as a medium in which to farm organisms, such as finfish, shellfish and aquatic plants, for example. The contribution of aquaculture to the livelihoods of rural communities was found to be negligible. “Small scale commercial” aquaculture projects were found to be more viable than “food security” projects. For "food security" projects, simple problems often resulted in project dysfunction or failure. Most projects had too many participants and the level of income per participant was very low. These "food security" type aquaculture projects were found to be unsustainable without ongoing technical support, and probably some structured “low interest” loans for set-up and input costs. The	Does WWBR count as aquaculture, and if so, which type? Community-public-private partnerships may be a suitable vehicle for promoting small-scale aquaculture projects. A public sector commitment on this scale requires clear policy objectives, sectoral plans and institutional coordination. The role of the public sector was analysed in this project in terms of emerging policy, the future of existing public sector aquaculture facilities, community public-private partnerships and interdepartmental coordination, and as such may prove useful to WWBR policy as well.

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				major weakness in all projects was a lack of training and experience in aquaculture and all projects required extension and technical support. Given the poor track record of the public sector in sustaining support to aquaculture projects, and the relative success of small-scale commercial projects, future policy should emphasise linkages to the existing private aquaculture sector by means of community-public-private partnerships.	
F	227	1081/1/04: Klusener CW, The development of a protein recovery technology at Sezela for the treatment of furfural plant azeotrope effluent with the simultaneous production of	2004	This document examines the use of filamentous fungi in the treatment of furfural effluent, producing a mycoprotein product for use in animal feed. The study focused on estimating a benchmark commercial value for the mycoprotein by evaluating it's use as an animal feed.	This study provides an excellent example of a process which could be incorporated in a WWBR, taking in an industrial effluent and simultaneously treating the WW and producing a salable product under non-sterile conditions.
F	228	1082/1/03: Christof LP, Further development of a biotechnological approach to the management of wastewaters from the pulp and paper industry	2003	Remediation of industrial wastewaters from the pulp and paper industry was investigated using biological methods such as pretreatment with enzymes, white-rot and mucoralean fungi. The wastewaters under study were derived from the extraction stage of the bleach plant as well as the spent sulphite liquor from the pulping stage of pulp production. Fermentation experiments for enzyme and gamma-linolenic production were carried out in shake flasks. Screening for best microbial sources was assessed according to levels of xylanase activity and single cell protein attained. The economical feasibility of the entire biobleaching technology using xylanases would be improved by utilising pulp mill wastewaters which at present are discarded as industrial waste.	Large WWBR potential. It has been demonstrated that implementation of the enzyme bleaching technology in the pulp and paper industry could improve the existing technology of pulp and paper manufacture in a cost-effective and environmentally friendly way. Trickling filters and RBC's were tested. The most efficient treatment system proved to be the rotating biological contactor where colour, bacterial growth inhibition levels, adsorbable organic halogen and chemical oxygen demand were decreased to a significant extent. Tall oil, which is a by-product derived from kraft mill spent liquor, could be utilised by selected fungi for production of high-value fatty acids such as gamma-linolenic acid.
F	229	939/1/03: Burton SG, Boshoff A, Foster I, Koteshwar K, Luke A, Mhlanga C, Nganwa P, Notshe T, Ryan D, Bioreactor systems for the conversion of organic compounds in industrial effluents to useful products.	2003	Focused on laccases, peroxidases and polyphenol peroxidases for the target groups of pollutants being phenolics, polyphenolics and related aromatic compounds. The research included investigations of enzyme production and biofilm growth as well as pollutant degradation. The enzymes in this study did not require cofactors such as NAD.	Significant WWBR potential. Work included fungal biofilms - Trametes versicolor and Neurospora crassa, which should be further investigated in WWBR application. Polyphenol oxidase (PPO) from mushrooms to synthesize cathechols should be investigated in the WWBR context.
F	230	TT 187/02: Rose PD, Salinity, Sanitation and Sustainability: A Study in Environmental Biotechnology and Integrated Wastewater Beneficiation in South Africa (Report 1) (and TT	2002	This report describes a twelve-year WRC investigation into an environmental biotechnology approach in the treatment of saline and sanitation wastewater, specifically focused on algal technologies.	The technologies used in this series of reports will be very applicable in WWBRs, and should inform research into any saline wastewaters.

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		188/02, TT 190/02, TT 191/02, TT 192/02, TT 196/02, TT 409/09)			
F	231	1054/1/01: Abbott G, Cultivation of high-value aquatic plants in restored urban wetlands for income generation in local communities ("new green" database)	2001	It is possible to cultivate economically valuable plants at high density in an altered urban wetland, and if growing conditions arc optimized then it should be possible for such a project to become a sustainable source of employment and wetland protection. Thus cultivation of economically valuable plants in wetlands can provide the economic incentives needed to ensure the continued preservation and rehabilitation of wetlands.	Relevance to the macrophyte bioreactor of a WWBR, and/or as it relates to Water sensitive urban design (WSUD). The Project Guidelines and Decision Support (Volume 1 of the HVAP project) should be used in determining the suitability of wetland sites for cultivation. Wetland culthation should ideally incorporate plants (in addition to the primary crop) which can fulfil multiple functions. However the environmental management requirements for wetlands will need lo be relaxed where possible to allow for cultivation of a number of useful plant species, some of which may not occur naturally in the wetland. A relaxation of the stringent standards of environmental protection imposed by the authorities will be required if altered wetlands are to become economically sustainable assets. Simple and low-cost solutions to irrigation, fertiliser and pesticide requirements should be used where possible.
F	232	182/1/89: Mitchell SA, The effective use of water by means of an algal aquaculture system	1989	The main aim of this project was to extend the technology of waste-water treatment by microalgae using organisms which would - (a) be cheap and easy to harvest so that the total suspended solids in effluent would conform to required standards; and (b) reclaim nitrogen from the waste stream in such a form that the biomass produced could be used as a supplement to stock feed. Systems employing a filamentous alga (Spirulina) and a grazing invertebrate (the fairy shrimp Streptocephalus macrourus) were compared. The long-term maintenance of a stable spirulina/zooplankton (Brachionus plicatili) polyculture is technically feasible with minimal agitation. It was found that sufficient agitation could be supplied with a power input of 10 kW/ha. It was also shown that it was to the Spirulina's advantange to be grown in polyculture with filter feeding invertebrates. These filter feeding invertebrates consumed the competing microalgae, and allowed the Spirulina to grow as a clean culture. Filter feeding invertebrates such as the brine shrimp Anemia and the water-flea Moina micrura were able to live successfully in Spirulina cultures while the Spirulina density was low, but rotifers such as Brachionus plicatilis and Hexarthra fennica were the only organisms able to live successfully in dense Spirulina cultures (Mitchell and Richmond, 1987).	Investigate this approach to 'DSP' in the WWBR, taking special note of the effect it would have on up- and downstream processes. Has any more up-to-date work been done in this field? While wastewater may be effectively treated by microalgae to remove dissolved solids, the algae must be removed from the effluent before the effluent will conform to the required effluent standards for total suspended solids. Harvesting the algae by flocculation, centrifugation or any other such method renders the process too expensive. This project investigated the possibility of using organisms that were large enough to be harvested easily to treat the wastewater. .

B SOUTH AFRICAN RESEARCH PUBLISHED IN JOURNALS

Table: B-1: Journal articles found on Scopus using keywords water, water treatment, South Africa, effluent and industrial

Category	Ref	Authors	Affiliation	Title of journal paper	Year of publication	Journal	Value of research in context of wastewater biorefineries	Shortcoming of research in context of WWBR / more work required
B	1	Simate, G.S.	School of Chemical and Metallurgical Engineering, University of the Witwatersrand	The treatment of brewery wastewater for reuse by integration of coagulation/flocculation and sedimentation with carbon nanotubes 'sandwiched' in a granular filter bed	2015	Journal of Industrial and Engineering Chemistry, 21, pp. 1277-1285.	This study deals with the integration of treatment systems and devices in order to reduce turbidity and chemical oxygen demand (COD) in brewery wastewater for re-use.	Lab scale study. Scale up work required.
A	2	Amdany, R., Chimuka, L., Cukrowska, E.	Molecular Sciences Institute, School of Chemistry, University of the Witwatersrand	Determination of naproxen, ibuprofen and triclosan in wastewater using the polar organic chemical integrative sampler (POCIS): A laboratory calibration and field application	2014	*Water SA*, 40 (3), pp. 407-414.	The study provides a method to determine the occurrence of two non-steroidal drugs and triclosan in wastewater using a polar organic chemical integrative sampler (POCIS)	Discrepancy in sample processing techniques
B	3	Welz, P.J [a], Palmer, Z.[ab], Isaacs, S.[a], Kirby, B.[b], le Roes-Hill, M. [a]	Biocatalysis and Technical Biology (BTB) Research Group, Cape Peninsula University of Technology	Analysis of substrate degradation, metabolite formation and microbial community responses in sand bioreactors treating winery wastewater: A comparative study	2014	Journal of Environmental Management, 145 (1), 147-156	The study yielded valuable insight that can be utilized in the design (configuration and operation) of full scale sand bioreactors.	

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B	4	Badejo, A.A., Ndambuki, J.M, Kupolati, W.K., Amuda, S.A.	Civil Engineering Department, Tshwane University of Technology	Performance of anaerobic digester-constructed wetlands system for brewery wastewater treatment	2014	Proceedings of the IASTED International Conference on Environment and Water Resource Management, AfricaEWRM 2014	The pilot plant study showed that Anaerobic Digester-constructed wetland (CW) combination has a high potential in brewery wastewater treatment.	
C	5	Mhlanga, F.T., Brouckaert, C.J.	Pollution Research Group, School of Chemical Engineering, University of KwaZulu-Natal	Characterisation of wastewater for modelling of wastewater treatment plants receiving industrial effluent	2013	*Water SA*, 39 (3), pp. 403-408.	The study provides a method to accurately characterise wastewater, focussing on the carbonaceous fraction. this information is instrumental in bioprocess modeling which aids in the design, modification and troubleshooting of wastewater treatment plants	This study focuses mainly on the carbonaceous fraction of wastewater, therefore further work needs to be carried out in order to characterise wastewater in terms of other important characteristics.
E	6	Nthumbi, R.M.[a], Catherine Ngila, J.[b], Moodley, B.[c], Kindness, A.[c], Petrik, L.[d]	[a]Kenyatta University, Kenya; [b]University of Johannesburg; [c]University of KwaZulu-Natal, School of Chemistry[d;] University of Western Cape	Application of chitosan/polyacrylamide nanofibres for removal of chromate and phosphate in water	2012	Physics and Chemistry of the Earth, 50-52, pp. 243-251.	The study focuses on the removal of phosphate and chromate which are prevalent in some industrial wastewaters. The work ultimately has applications making water contaminated with these anions safe for human consumption.	The work carried out was limited to lab scale experiments - thus further work will be required in order to determine if the methods developed can be applied on the scale required for a WWBR.
B	7	Simate, G.S.[a], Iyuke, S.E.[a], Ndlovu, S.[a], Heydenrych, M.[b]	[a] School of Chemical and Metallurgical Engineering, University of the Witwatersrand [b] Department of Chemical Engineering, University of Pretoria	The heterogeneous coagulation and flocculation of brewery wastewater using carbon nanotubes	2012	*Water Research*, 46 (4), pp. 1185-1197.	The ability of carbon nanotubes to act as a flocculant and/or coagulant is tested and compared to that of ferric chloride and it was found that traditional ferric chloride to be a more effective coagulant in all cases.	

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B	8	De Jager, D.[a], Sheldon, M.S.[a], Edwards, W.[b]	[a] Department of Chemical Engineering, Cape Peninsula University of Technology [b] Atl-Hydro, Fish Hoek, Cape Town, 8000, South Africa	Membrane bioreactor application within the treatment of high-strength textile effluent	2012	Water Science and Technology, 65 (5), pp. 907-914.	A dual-stage membrane bioreactor system with ultrafiltration modules was designed and used to successfully treat high-strength textile effluent to well below required discharge standards.	Such a reactor system should be tested at a larger scale using different types of effluents in order to determine of the same positive results can be obtained.
E	9	Opeolu, B.O.[a], Bamgbose, O.[b], Fatoki, O.S.[a]	[a] Department of Chemistry, Cape Peninsula University of Technology [b] Department of Environmental Management and Toxicology, University of Agriculture, Abeokuta, Nigeria	Zinc abatement from simulated and industrial wastewaters using sugarcane biomass	2011	*Water SA*, 37 (3), pp. 313-320.	This study assessed the potential of sugarcane biomass to remove zinc from standard solutions and industrial (paint and textile) wastewaters. Sugarcane biomass is therefore a potential alternative to expensive synthetic resins. Its biodegradability makes disposal environmentally friendly.	There is the need to further study the biomass in flow-through systems for industrial applicability.
B	10	Lin, J., Harichund, C.	School of Biochemistry, Genetics, and Microbiology, University of KwaZulu- Natal	Industrial effluent treatments using heavy-metal removing bacterial bioflocculants	2011	*Water SA*, 37 (2), pp. 265-270.	Bioflocculants were shown to successfully treat a heavy metal waste stream, removing several heavy metals effectively and simultaneously. The bioflocculant further removed almost all bacteria present and greatly reduced the turbidity of the wastewater.	The study suggests that that the use of bioflocculants may be effluent dependant. Therefore further study is recommended in order to determine the optimum conditions.

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B	11	Mack, C.L.[a], Wilhelmi, B.[a], Duncan, J.R.[a], Burgess, J.E.[a b]	[a] Department of Biochemistry Microbiology and Biotechnology, Rhodes University [b] Water Research Commission	Biosorptive recovery of platinum from platinum group metal refining wastewaters by immobilised Saccharomyces cerevisiae	2011	Water Science and Technology, 63 (1), pp. 149-155.	*Saccharomyces cerevisiae* has been found capable of sorbing numerous precious and base metals, and is a cheap and abundant source of biomass.	The sorption mechanism was found to be a chemical reaction, which made effective desorption impossible. When applied to PGM refinery wastewater, two key wastewater characteristics limited the success of the sorption process; high inorganic ion content and complex speciation of the platinum ions. The results proved the concept principle of platinum recovery by immobilised yeast biosorption and indicated that a more detailed understanding of the platinum speciation within the wastewater is required before biosorption can be applied.
B	12	Tabrizi, M.T.F., Glasser, D., Hildebrandt, D.	Centre of Material and Process Synthesis, School of Chemical and Metallurgical Engineering, University of the Witwatersrand	Wastewater treatment of reactive dyestuffs by ozonation in a semi-batch reactor	2011	Chemical Engineering Journal, 166 (2), pp. 662-668	The use of ozonation was shown to be effective in completely decolourising and partially oxidizing textile dyes.	More work is required to model the complex ozonation process. Such a model would be required in order to design an industrial decolouration plant.
B	13	Oboirien, B.O., Molokwane, P.E., Chirwa, E.M.N.	Department of Chemical Engineering, University of Pretoria	Bioremediation of organic pollutants in a radioactive wastewater	2009	Proceedings of the ICEM2007 - 11th International Conference on Environmental Remediation and Radioactive Waste Management, (PART B), pp. 873-876	[relevance - for radioactive waste]	

Category	Ref	Authors	Affiliation	Title of journal paper	Year of publicatio n	Journal	Value of research in context of wastewater biorefineries	Shortcoming of research in context of WWBR / more work required
C	14	Mhlanga, F.T.[a], Brouckaert, C.J.[a], Foxon, K.M.[a], Fennemore, C.[b], Mzulwini, D.[a], Buckley, C.A.[a]	[a] Pollution Research Group, School of Chemical Engineering, University of KwaZulu-Natal [b] eThekwini Water Services, 3 Prior Road, Durban 4041, South Africa	Simulation of a wastewater treatment plant receiving industrial effluents	2009	*Water SA*, 35 (4), pp. 447-454	A process model simulating the treatment of municipal wastewater, with a high proportion of industrial effluents was developed.	Perhaps such a process model could be adapted to a WWBR context, such that the entire process could be simulated to either aid in the design or operation of a WWBR.
B	15	Onyancha, D.[a], Mavura, W.[b], Ngila, J.C.[c], Ongoma, P.[b], Chacha, J.[d]	[a] Department of Chemistry, Nelson Mandela Metropolitan University [b] Department of Chemistry, Egerton University [c] School of Chemistry, University of KwaZulu Natal [d] Department of Chemistry, Jomo Kenyatta University of Agriculture and Technology	Studies of chromium removal from tannery wastewaters by algae biosorbents, Spirogyra condensata and Rhizoclonium hieroglyphicum	2008	Journal of Hazardous Materials, 158 (2-3), pp. 605-614	Algae biosorbents were used to effectively remove chromium from wastewater, which is of concern primarily to the tanning industry.	The scalability of the use of algae biosorbents to remove chromium from wastewaters requires further investigation.
B	16	Strong, P.J.[a b], Burgess, J.E.[a]	[a] Department of Biochemistry, Microbiology and Biotechnology, Rhodes University [b] CSIR Biosciences,	Fungal and enzymatic remediation of a wine lees and five wine-related distillery wastewaters	2008	*Bioresource Technology*, 99 (14), pp. 6134-6142	Wine distillery wastewaters were treated using fungi resulting in a reduction in COD, phenolic compounds and colour. The treatment of the wastewater with laccase reduced the presence of phenolics but increased the colour significantly.	The fungal treatment showed promise in treating wine distillery wastewater, the use of the same fungal treatment should be investigated to treat other types of wastewaters.

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D	17	Rava, E.[a d], Schoeman, J.J.[a], Allison, P.J.[b], Dilsook, V.[c]	[a] University of Pretoria, Department of Chemical Engineering, Water Utilisation Division [b] Buckman Laboratories (Pty) Ltd (Hammarsdale) [c] Sappi Management Services - Technology Centre [d] Buckman Laboratories (Pty) Ltd (Bedfordview)	Management of hydrogen sulphide generation at a Kraft mill effluent plant	2008	*Water SA*, 34 (2), pp. 245-248	Sulphate reducing bacteria were successfully used to reduce the aqueous levels of H2S in Kraft mill wastewater, thereby reducing the odours emanating from the mill's effluent treatment plant.	The use of sulphate reducing bacteria could possibly employed to reduce odours from other effluents containing H2S.
D	18	Strong, P.J., Burgess, J.E.	Department of Biochemistry, Microbiology and Biotechnology, Rhodes University	Bioremediation of a wine distillery wastewater using white rot fungi and the subsequent production of laccase	2007	Water Science and Technology, 56 (2), pp. 179-186	*Trametes pubescens* MB 89 was shown to greatly improve the quality of wine distillery wastewater, which is known to be toxic to most biological treatment systems, while at the same time producing laccase.	The use of *Trametes pubescens* MB 89 to treat other types of wastewaters while simultaneously producing laccase should be furterh investigated.
E	19	Potgieter-Vermaak, S.S.[a], Potgieter, J.H.[b], Monama, P.[c], Van Grieken, R.[a]	[a] Department of Chemistry, University of Antwerp [b] School of Chemical and Metallurgical Engineering, University of the Witwatersrand [c] Department of Chemistry, Tshwane University of Technology	Comparison of limestone, dolomite and fly ash as pre-treatment agents for acid mine drainage	2006	*Minerals Engineering*, 19 (5), pp. 454-462	The study reveals significant savings can be achieved by treating acid mine drainage when lime is replaced by either dolomite or fly ash.	The possibility of using fly ash and/or dolomite should be investigated when there is the need to raise the pH of wastewaters required to be treated.

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E	20	Jonker, A.[a c], Potgieter, H.[b d]	[a] Tshwane University of Technology [b] University of Witwatersrand [c] Department of Chemistry and Physics, Tshwane University of Technology [d] School of Process and Materials Engineering, University of the Witwatersrand	Physical properties of composites made from secondary cementitious materials with reference to their suitability for water filters	2005	Proceedings of the International Conference on Application of Codes, Design and Regulations, pp. 99-107	Selected waste (cementitious material) generated by the power generation, fertilizer and steel industries have shown promise in being used as a filter medium to treat industrial wastewater	The use of waste cementitious material to potentially remove various contaminants from industrial effluents should be further investigated to confirm their suitability in removing contaminants from industrial wastewater.
B	21	Lalbahadur, T.[a], Pillay, S.[b], Rodda, N.[b], Smith, M.[b], Buckley, C.[c], Holder, F.[a], Bux, F.[a], Foxon, K.[c]	[a] Centre for Water and Wastewater Technology, Durban Institute of Technology [b] School of Life and Environmental Sciences, Biochemical Research Group, University of Natal [c] School of Chemical Engineering, Pollution Research Group, University of Natal	Microbiological studies of an anaerobic baffled reactor: Microbial community characterisation and deactivation of health-related indicator bacteria	2005	Water Science and Technology, 51 (10), pp. 155-162	Moderate success in treating domestic wastewater was achieved using an anaerobic baffled reactor was achieved.	The reactor discharge was not below required contaminant levels and this was possibly due to hydraulic load limitations.
E	22	Esau, A.[a], Petersen, F.[b]	[a] Department of Chemical Engineering, Cape Technikon [b] Mintek, South Africa	Biosorption technologies for water treatment	2004	Waste Management and the Environment II, pp. 587-593	Biosorption of heavy metals such as Pb and Cu was shown to be effective (up to 100% removal) with fast kinetics, using eklonia maxima (brown seaweed). Using biomaterials is more cost effective than industrially used resins.	The work was conducted on a very small scale - thus the scalability of such biomaterials needs to be further investigated.

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E	23	Coopmans, E.J.A., Schwarz, H.P	Explochem Water Treatment (Pty) Ltd	Clarification as a pre-treatment to membrane systems	2004	*Desalination*, 165 (SUPPL.), pp. 177-182	Explochem Water Treatment has successfully design and built large scale water treatment plants that are effective in treating eutrophic algae laden water to drinking water standards.	
D	24	Boshoff, G.[a] , Duncan, J.[b] , Rose, P.D.[b]	[a] Environ. Engineering Research Centre, School of Civil Engineering, Queens University Belfast, Stranmillis Road, Belfast [b] Goldfields Biotechnology Laboratory, Dept. of Biochem. and Microbiology, Rhodes University	Tannery effluent as a carbon source for biological sulphate reduction	2004	*Water Research*, 38 (11), pp. 2651-2658	Sulphate removal of 60-80% was achieved using tannery effluent in pilot scale stirred tank reactor (STR), upflow anaerobic sludge blanket (UASB), and trench reactor (TR).	Although sulphate removal was achieved, COD removal rates decreased by 25%.
C	25	Gianadda, P., Brouckaert, C.J., Sayer, R., Buckley, C.A.	Pollution Research Group, School of Chemical Engineering, University of Natal	The application of pinch analysis to water, reagent and effluent management in a chlor-alkali facility	2002	Water Science and Technology, 46 (9), pp. 21-28	The concepts of water pinch analysis is introduced with the aim of reducing the amount of utility and process water used in the chlor-alkali process.	Water pinch analysis could potentially be used to maximise water treatment efficiency.
B	26	Mkhize, S.P., Bux, F	Ctr. for Water and Wastewater Res., Technikon Natal	Assessment of activated sludge to remediate edible-oil effluent	2001	South African Journal of Science, 97 (9-10), pp. 380-382	Anaerobic/aerobic sequencing batch reactor was used to remediate edible-oil effluent - greatly reducing COD as well as phosphates present.	Further investigation needs to be done to realise the full scale-up potential of this process when treating edible oil effluent. There is the possibility that this same reactor system could be used to treat other types of oil laden effluents.

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D	27	Greben, H.A., Maree, J.P., Singmin, Y., Mnqanqeni, S	Division of Water, Environment and Forestry Technology, CSIR	Biological sulphate removal from acid mine effluent using ethanol as carbon and energy source	2000	Water Science and Technology, 42 (3-4), pp. 339-344.	A biological sulphate removal process has been developed for the treatment of sulphate-rich industrial effluents, where sulphate is converted via sulphide to sulphur in an anaerobic single-stage reactor. Ethanol is used as carbon and energy source.	
B	28	Bell, J., Plumb, J.J., Buckley, C.A., Stuckey, D.C.	Sci., School of Chemical Engrg., Univ of Natal, Durban,	Treatment and decolorization of dyes in an anaerobic baffled reactor	2000	Journal of Environmental Engineering, 126 (11), pp. 1026-1032.	Decolorization of industrial wastewater from a food dye manufacturer in an anaerobic baffled reactor. Reduction in COD of 70% and color reduction of about 90% was achieved	Lab-scale study. Initially the tartrazine was not readily decolorized; however, decolorization improved with acclimation of the biomass
A	29	Pitman, A.R.[a] , Boyd, L.A.[b]	[a] Wastewater, Gtr. Johannesburg M., Braamfontein, [b] Health and Scientific Services, Gtr. Johannesburg Metropol. Council, Braamfontein,	Transforming local government wastewater departments — From adversary to industrial partner	1999	Water Science and Technology, 39 (10-11), pp. 39-45.	The need to remove nutrients from wastewater by biological means and dispose of sludge by-products in an efficient manner has prompted the Greater Johannesburg Metropolitan Council to adopt a new approach to the management of industrial discharges. Proposed rebate on the normal discharge tariff will encourage the discharge of industrial effluents having a high readily biodegradable concentration (which would assist the BNR process).	Those effluents having high concentrations of heavy metals (which would degrade the reuse value of sludge by-products) would be discouraged by means of an additional penalty above the normal discharge tariff.

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D	30	Zhao, M., Duncan, J.R., Van Hille, R.P.	Dept. of Biochem. and Microbiology, Rhodes University	Removal and recovery of zinc from solution and electroplating effluent using *Azolla filiculoides*	1999	*Water Research*, 33 (6), pp . 1516-1522	A method to recover zinc from electroplating effluent using Azolla filiculoides was investigated using batch columns. The mechanical stability and flow permeability of Azolla filiculoides. Complete desorption of the bound zinc was also achieved.	Azolla filiculoides could be potentially used to recover zinc from other effluents, such as ARD containing zinc.
B	31	Edwards, W.[a], Bownes, R.[a], Leukes, W.D.[a], Jacobs, E.P.[b], Sanderson, R.[b], Rose, P.D.[a], Burton, S.G.[a]	[a] Goldfields Biotechnology Centre, Dept. Biochem. Microbiol., Rhodes U. [b] Institute for Polymer Science, Stellenbosch University	A capillary membrane bioreactor using immobilized polyphenol oxidase for the removal of phenols from industrial effluents	1999	Enzyme and Microbial Technology, 24 (3-4), pp. 209-217.	A capillary membrane bioreactor has been developed and tested for the removal of phenolic compounds from synthetic and industrial effluents. Almost complete removal of the colored quinones and associated polymers from the permeate was observed.	
D	32	Atkinson, B.W., Bux, F., Kasan, H.C.	Ctr. for Water and Wastewater Res., Department of Biotechnology, Technikon Natal	Considerations for application of biosorption technology to remediate metal-contaminated industrial effluents	1998	*Water SA*, 24 (2), pp. 129-135.	A pilot-plant feasibility study, using waste activated sludge to bioremediate a metal plating effluent, showed that the currently used method of chemical precipitation is more cost-effective. This paper describes the factors that must be considered when selecting bioremediation as a cleanup technology for inorganics.	

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D	33	Atkinson, B.W., Bux, F., Kasan, H.C.	Department of Biotechnology, Technikon Natal	Bioremediation of metal-contaminated industrial effluents using waste sludges	1996	*Water Science and Technology*, 34 (9 pt 5), pp. 9-15	Activated sludge was used to biosorb metal contaminated effluent on a laboratory scale using up-flow column bioreactors. The average adsorptive capacity of the biomadd was 80%, eithing the first 15 minutes.	This same activated sludge process could be potentially used to recover metals from other metal contaminated effluents, such as ARD. However, scale up issues would potentially have to be dealt with.
B	34	Schoeman, J.J., Steyn, A., Scurr, P.J.	Watertek, CSIR	Treatment using reverse osmosis of an effluent from stainless steel manufacture	1996	*Water Research*, 30 (9), pp . 1979-1984	The work showed that it is possible to treat neutralized spent acid effluent (seepage) effectively using reverse osmosis for effluent volume reduction, water recovery and pollution control.	Cost remains a significant factor when considering any type of RO technology. RO is an option for very difficult to treat effluents and could possibly used as a final polishing step.
A	35	Haarhoff, J.[a] , Van Der Merwe, B.[b]	[a] Department of Civil Engineering, Rand Afrikaans University [b] City Engineer's Department, Windhoek, Namibia	Twenty-five years of wastewater reclamation in Windhoek, Namibia	1996	*Water Science and Technology*, 33 (10-11), pp. 25-35	A comprehensive review of the wastewater water reclamation plant in Windhoek. The paper details the systems used and the results obtained by the plant over the past 25 years and the plans to expand its capacity from 4800 to 21000 m^3/day.	The review can provide good insight of a working water reclamation plant that has been successful and operating on large scale.
C	36	Maree, J.P., Du Plessis, P	Division of Water Technology, CSIR	Neutralization of acid mine water with calcium carbonate	1994	*Water Science and Technology*, 29 (9), pp. 285-296	Calcium carbonate is investigated as an alternative to lime for the neutralization of acidic effluent with varying degrees of success. Calcium carbonate is an attractive alternative given its low cost, simple doing system required and low solubility at pH less than 7.	

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B	37	Howgrave-Graham, A.R., Isherwood, H.A., Wallis, F.M.	Dept. Microbiology Plant Pathology, University of Natal,	Evaluation of two upflow anaerobic digesters purifying industrial wastewaters high in organic matter	1994	Water Science and Technology, 29 (9), pp. 225-229	Two full-scale anaerobic digesters, one a clarigester purifying a maize processing wastewater and the other with an upflow anaerobic sludge blanket (UASB) configuration treating brewery effluent contained well setting, granular sludges efficient in pollutant removal.	
C	38	Kilani, J.S.	Univ of Durban-Westville, Durban	Compatibility study of the effects of dairy and brewery effluents on the treatability of domestic sewage	1993	*Water SA*, 19 (3), pp. 247-252.	The results indicate that the dairy and the brewery wastes have no adverse effect on the treatability of the domestic sewage. Furthermore, the effluents from the 5 ponds have BOD/COD ratios within ranges that are generally accepted as indicating a high degree of biodegradability. They would therefore not be expected to have any adverse effect on the efficiency of secondary biological treatment processes.	

Category	Ref	Authors	Affiliation	Title of journal paper	Year of publicatio n	Journal	Value of research in context of wastewater biorefineries	Shortcoming of research in context of WWBR / more work required
B	39	Jackson-Moss, C.A., Maree, J.P., Wotton, S.C.	Division of Water Technology, CSIR	Treatment of bleach plant effluent with the biological granular activated carbon process	1992	Water Science and Technology, 26 (1-2), pp. 427-434.	Bleach plant effluent from the pulp and paper industry was treated by means of the anaerobic biological granular activated carbon process. It was found that over 50% of the COD and colour could be successfully removed from this effluent. The adsorptive capacity of the activated carbon was extended as a result of microbial activity inside the anaerobic reactor. The results of this investigation suggest that the anaerobic biological granular activated carbon process could be used to alleviate the pollution problems experienced by the pulp and paper industry.	

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B	40	Cowan, J.A.C., MacTavish, F., Brouckaert, C.J., Jacobs, E.P.	Steffen, Robertson and Kirsten Inc, Johannesburg, South Africa	Membrane treatment strategies for red meat abattoir effluents	1992	*Water Science and Technology*, 25 (10) , pp. 137-148.	These treatment techniques have now been lifted from the research phase into commercial application on small scale (25m3/d) using full size modules. The South African Abattoir Corporation, as the major representative of the industry in South Africa, has undertaken to assess the value of membrane treatment processes as a part of a number of effluent treatment strategies. Ultrafiltration will consistently remove 90% COD, 85% phosphate from the effluent, and provide a relatively non-fouling feed for reverse osmosis which produces a high quality reusable water for abattoir use.	
B	41	Buckley, C.A.	Pollution Research Group, Department of Chemical Engineering, University of Natal,	Membrane technology for the treatment of dyehouse effluents	1992	*Water Science and Technology*, 25 (10) , pp. 203-209	In this paper, dye chemistry is summarized and ten of the most commonly used dye types are identified. For color removal purposes the dyes are grouped into three classes. Four membrane processes are described which have been used in South Africa for the treatment of dyehouse effluents.	
B	42	Strohwald, N.K.H., Ross, W.R.	Membratek (Pty) Ltd, Noorder Paarl, South Africa	Application of the ADUFR process to brewery effluent on a laboratory scale	1992	*Water Science and Technology*, 25 (10) , pp. 95-105	An anaerobic digestion – ultrafiltration (ADUFR) unit successfully treated brewery effluent on a lab scale, reducing COD by up to 99%, with no membrane fowling.	

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E	43	Meyer, V., Carlsson, F.H.H., Oellermann, R.A.	Division of Water Technology, CSIR, PO Box 395, Pretoria	Decolourization of textile effluent using a low cost natural adsorbent material	1992	*Water Science and Technology*, 26 (5-6), pp. 1205-1211.	colour from textile-plant effluents, tests were run using several low cost natural adsorbent materials including vermiculite, sawdust, barbecue charcoal, maize stalks, sand, rice husks and peatmoss. With the exception of vermiculite, more than 50% of the colour was removed from the wastewater, with barbecue charcoal and rice husks showing the best adsorptive qualities (67% and 65% respectively). Under simulated industrial conditions on a laboratory scale a fixed-bed reactor was used to investigate the adsorption capacity of barbecue charcoal with respect to colour removal. An average of 28% of colour was removed at a hydraulic retention time (HRT) of 1.6 h over a period of 25 days. The effect of pH on the adsorptive capacity with respect to colour removal and represents a relatively cheap adsorbent material compared to conventionally used granular activated carbon.	
B	44	Maree, J.P., Hulse, G., Dods, D., Schutte, C.E.	Division of Water Technology, CSIR	Pilot plant studies on biological sulphate removal from industrial effluent	1991	*Water Science and Technology*, 23 (7-9), pp. 1293-1300	A biological sulphate removal process was developed for the treatment of sulphur rich industrial effluents.	

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B	45	Maree, J.P., Strydom, W.F.	National Institute for Water Research, CSIR	Biological sulphate removal from industrial effluent in an upflow packed bed reactor	1987	*Water Research*, 21 (2), pp . 141-146	The removal of sulphate (by conversion to sulphide then elemental sulphur) by two bacteria has been shown to symbiotically occur in a upflow packed bed reactor.	
	Using the keyword search terms wastewater biorefinery and SA as affiliate							
F	46	Singh, B., Guldh, A., Singh, P., Rawat, I., Bux, F., Singh, A.	Centre for Environmental Sciences, Central University of Jharkhand, Ranchi, India and Institute for Water and Wastewater Technology, Durban University of Technology	Sustainable production of biofuels from microalgae using a biorefinary approach	2015	*Applied Environmental Biotechnology: Present Scenario and Future Trends, 115-128*	*The value added product derived from biorefinery basket includes pigments, nutraceuticals, and bioactive compounds. The use of industrial refusals for biomass production includes wastewater as nutrient medium and utilization of flue gases (CO2) as the carbon source for culture of microalgae. These processes have the potential to reduce fresh water footprint and carbon footprint.*	

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F	47	Rawat, I., Bhola, V., Kumar, R.R., Bux, F	Institute for Water and Wastewater Technology, Durban University of Technology	Improving the feasibility of producing biofuels from microalgae using wastewater	2013	Environmental Technology (United Kingdom), 34 (13-14), pp. 1765-1775.	The use of a biorefinery approach sees the production costs reduced greatly due to utilization of waste streams for cultivation and the generation of several potential energy sources and value-added products while offering environmental protection. The use of wastewater as a production media, coupled with CO 2 sequestration from flue gas greatly reduces the microalgal cultivation costs. Conversion of residual biomass and by-products, such as glycerol, for fuel production using an integrated approach potentially holds the key to near future commercial implementation of biofuels production.	
F	48	Rawat, I., Ranjith Kumar, R., Mutanda, T., Bux, F.	Institute for Water and Wastewater Technology, Durban University of Technology	Dual role of microalgae: Phycoremediation of domestic wastewater and biomass production for sustainable biofuels production	2011	Applied Energy, 88 (10), pp. 3411-3424	This paper discusses current knowledge regarding wastewater treatment using HRAPs and microalgal biomass production techniques using wastewater streams. The paper discusses biodiesel production via transesterification of the lipids and other biofuels such as biomethane and bioethanol which are described using the biorefinery approach.	

C ANALYSIS OF SOUTH AFRICAN WASTEWATER STREAMS FOR BIOREFINERY FEEDSTOCK

C.1 Conversion Calculations for Concentration of Carbon, Nitrogen and Phosphorous

C.1.1 Concentration of carbon

C.1.2 Concentration of nitrogen

C.1.3 Concentration of phosphorus

C.2 General Data for Industrial Wastewaters

C.2.1 Summary data used in this report for industrial wastewaters

C.2.2 Additional general data for industrial wastewaters

C.3 Municipal Wastewater (Section 4.2)

C.4 Data for Specific Industrial Wastewaters (Section 4.3)

C.4.1 Pulp and paper industry (Section 4.3.1)

C.4.2 Petroleum industry (Section 4.3.2)

C.4.3 Poultry abattoirs industry (Section 4.3.3)

C.4.4 Red meat abattoirs industry (Section 4.3.3)

C.4.5 Dairy industry (Section 4.3.3)

C.4.6 Soft drinks industry (Section 0)

C.4.7 Alcoholic beverage industry (Section 0)

C.4.8 Edible oil (Section 0)

C.4.9 Canning (Section 0)

C.4.10 Confectionery industry (Section 0)

C.4.11 Textiles industry (Section 4.3.5)

C.4.12 Cleaning products manufacture (Section 4.3.5)

D PRELIMINARY EXPERIMENTAL EVALUATION OF SELECTED BACTERIAL BIOPRODUCT

D.1 Materials and Methods for Poly-γ-Glutamic Acid Studies

D.1.1 Inoculum

D.1.2 Medium composition

D.1.3 Bioreactor conditions

D.1.4 Analyses

D.2 Temperature Study Using Isolate 1 (*Bacillus subtilis)*

D.2.1 Growth study

D.2.2 PGA productivity study

D.2.3 Recommendations for further studies

D.3 Material and Method for Growth Curve Base Case Using Isolate 1 (Bacillus subtilis)

D.3.1 Inoculum

D.3.2 Medium composition

D.3.3 Bioreactor conditions

D.3.4 Analyses

D.4 Base Case Results

D.5 Recommendations for Further Study

E PRELIMINARY EXPERIMENTAL EVALUATION OF SELECTED BACTERIAL BIOREACTORS

E.1 Bioreactor Design and Commissioning

E.1.1 MBBR

E.1.2 Aerobic Granular Sludge in an SBR

E.1.3 RBC

E.2 Initial Performance Studies for the Moving Bed Bioreactor

E.2.1 Tracer tests and mixing studies

E.2.2 Initial commissioning of MBBR

E.3 Current Experimental Work

E.3.1 Acquiring new carriers

E.3.2 Acclimatisation of K3 carriers

E.4 Ongoing Experimental Work

F SUPPLEMENTARY MASS BALANCE TABLES FOR BIOREACTOR TRAINS

F.1 Nitrogen and phosphorus mass balances

F.2 Mass Balance for Algal Bioreactor

F.3 Mass Balance for Macrophyte Bioreactor

F.4 Mass Balance for Solids Bioreactor

G SUPPLEMENTARY DATA FOR SELECTION OF MASS BALANCE FACTORS

G.1 Supporting data for Section 8.1 Unit Mass Balances

G.1.1 Bacterial bioreactor factors for mass balances

G.1.2 Algal bioreactor factors for mass balances

G.1.3 Macrophyte bioreactor factors for mass balances

G.1.4 Solids bioreactor factors for mass balances

G.2 Supplementary Information for Section 8.2

H CREATING SANKEY DIAGRAMS FOR VISUALISATION OF WASTEWATER BIOREFINERY MASS BALANCES

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H.1 Procedure to Display Sankey Files

H.2 Code Used to Import Data into Sankey (.json file)

H.3 Sankey Code Used to Process Data into Diagram (.html file)

H.4 Supporting Data that can be Accessed from the Internet