TRANSFORMATIVE APPROACHES IN MANAGING HUMAN WASTE AND WASTEWATER BY REFRAMING NUTRIENT RECOVERY FROM INNOVATIVE SANITATION TECHNOLOGIES AS INTEGRAL COMPONENTS OF FARMING AND FOOD SYSTEMS

Report to the
Water Research Commission

by

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This report emanates from a project titled: "*Transformative approaches in managing human waste and wastewater by reframing nutrient recovery from innovative sanitation technologies as integral components of farming and food systems*" (WRC project no. C2021/2022-00603).

EXECUTIVE SUMMARY

Transformative approaches in agriculture are needed to change the way nutrient recovery from wastewater and human excreta is perceived as an addition to sanitation technologies for sustainable waste management. Reframing human excreta management as integral components of farming and food systems should be integrative and adaptive and allow novel partnerships, cross sectoral and multi-stakeholder relationships when designing, adapting and scaling up innovative sanitation technologies that allow nutrient recycling. This integrative and adaptive component has often been absent in most research initiatives being undertaken on nutrient recovery and reuse in agriculture.

The project investigated (i) the local community attitudes, perceptions, and barriers (legal and economic costs) towards the use of waste-based fertiliser products for crop production, (ii) application of advanced waste treatment methods in human wastes such as excreta materials and activated sludge, monitoring and evaluating the availability of micropollutants and pathogens, and their subsequent prevalence in soils and possible transfer into plant tissues, (iii) recovered bioresources such as struvite (fertilizer) and biosolids from the human wastes such as excreta materials and activated sludge, (iv) grew selected crops to test the fertiliser value of the waste-based bioresource products, impacts on soils, crops, and the environment, and (v) proposed small-scale processes for value addition of locally produced crops using the recovered waste-based bioresource products.

A scoping review was done following Joanna and Briggs Institute methods. The review investigated the extent to which transformative approaches may be applied to facilitate transition from traditional unsustainable linear materials flow to a circular bioeconomy. The circular bioeconomy model has a component of agricultural end-use along the sanitation value chain. The review further discussed potential barriers that might impede integration of sanitation-based fertilisers for sustainable agriculture in South African communities and beyond. One of the findings was that the South African legal framework does not prohibit the agricultural use of Human Excreta Derived Fertilisers (HEDFs). The major challenge is lack of clarity on whether farmers should produce crops using HEDFs and the dilemma for retailers to accept the produce in fear to spoil their reputation. Addressing this issue needs integration of all governmental organisations and relevant stakeholders to establish a policy allowing the use of HEDFs for food crop production. Social perceptions and attitudes towards the use of HEDFs are not prohibitive unless people are assured that the products are safe as endorsed by relevant authorities. Best practices are not a barrier due to the availability of South African guidelines guiding on the use of three excreta streams with special focus on legal and technical requirements, managing health risks and protecting the environment. However,

management of chemicals of emerging concern remain a grey area that needs attention. Otherwise, the use of HEDFs can be done following existing standards and norms. Economic viability of excreta reuse interventions is a challenge for small scale entrepreneurs who are unable to produce to meet economies of scale. The competition for fertilisers produced using conventional- and energy-intensive processes is higher than vast circular bioeconomy interventions. A strong motivation to convince farmers to commit is needed. This can be done through education and awareness on environmental, public and financial benefits of sustainable waste management with special focus on cleaner environment, reduced public health risks and resource extraction efficiency. When it comes to financial benefits, in this case profitability, access to niche markets is an option. This is still at the policy level as the European Union is considering reviewing policies that link their circular bioeconomy paradigms and practices with their trading partners including Africa.

Transitioning to a CBE needs a paradigm shift from operating within silos to transdisciplinarity and collaborations in innovation platforms. The communal farmers, women and youth owned cooperatives were engaged to co-identify challenges being faced in their food production systems. The co-identification and characterisation of the stakeholders needed to deal with respective challenges across the food and waste value chains was done. A sound participatory research roadmap for co-testing the practical applicability of using HEDFs for agriculture within the South African context was co-developed. The women and youth-owned cooperatives from Vulindlela, Appelsbosch and Sobantu communities were identified and engaged. The challenges faced by small scale farmers that were identified during the participatory rural appraisals included theft, lack of title deeds, financial and technical limitations to operate viable agribusiness projects, lack of information on agricultural value addition and reliable markets. These challenges can be addressed if the following stakeholders commit and contribute to supporting circular bioeconomy interventions: regulatory boards (South African Bureau of Standards; SABS and Consumer Goods Council of South Africa; CGSA), governmental institutions (Department of Agriculture Land Reform and Rural Development; DALRRD, Department of Forestry Fisheries and Environment; DFFE, Department of Water and Sanitation; DWS, Department of Trade Industry and Competition; DTIC, Department of Women Youth and People with Disabilities; DWYPD and Department of Health; DOH), private entities (Commercial farmers, Retailers) and local municipalities. The proposed activities were testing HEDFs coming from different innovations on selected crops, assessing the production of co-compost using VIP sludge mixed with green waste, improving the DEWATS treatment through integration of advanced methods, and assessing and implementing sustainable small scale processing entities for identified cooperatives and urine treatment at identified school. There were various lessons learnt from the engagement process. Although communal farmers were positive and enthusiastic about participating in CBE activities their final commitments were mainly obstructed by the interests of community champions and absence of clear profitable business models.

There are perceived health risks associated with the use of HEDFs. Agricultural use of HEDFs should be tailored around maximising the associated benefits while minimising the perceived risks. The World Health Organization guideline encourages the treatment of human excreta and application of multi barrier approach to ensure that everyone across the waste and food value chain is protected from health risks. Stakeholders that are relevant to advanced human excreta treatment technologies were identified and engaged in this section. The application of advanced treatment methods for human excreta materials including activated sludge. Monitoring and evaluating the potential flows of micropollutants and pathogens across the sanitation and food value chains was conceptualised. A preliminary study was done to apply advanced treatment methods to treat domestic wastewater for unrestricted agricultural use. Comparisons between two wastewater treatment methods (UV photocatalysis with TiO_2 and ozonolysis) showed that ozonolysis was the best advanced oxidation process that would fully treat the AF effluent to meet the required wastewater standards for unrestricted agricultural use.

Having the best technologies to recover nutrients for safe agricultural use is important. Human excreta treatment removes pollutants of health concerns while improving or maintaining the agronomic value of the resulting product. For example, co-composting produces a sterile product used as a soil conditioner while urine treatment focuses on recovering nutrients. In cognizance of social dynamics around the safety and aesthetic value of HEDFs, production of a legally acceptable fortified organic fertiliser may increase acceptability and promote adoption of the circular bioeconomy products. The study used co-compost to produce fortified products containing struvite and dried urine. These were assessed for legal compliance with the South African Fertilisers, Farm Feeds, Agricultural remedies and Stock remedies Act, 1947 (Act no 36 of 1947). Community considerations with regards to their participation in fertiliser production, constraints for viable business models and institutional recommendations to spearhead the HEDFs use were discussed. Fortification of sewage sludge/green waste co-compost with dried urine increased its fertiliser value in compliance with the South African Fertilisers, Farm Feeds, Agricultural Remedies and Stock remedies Act no 36 of 1947 for registration as an “organic fertiliser mixture”. The fortified organic fertiliser mixture had very high pH which made it a good alkaline fertiliser for acidic soils that are predominant in Sub Sahara region. Cost considerations, economies of scale and identification of strategic locations to establish the treatment plants are crucial for the economic viability of such enterprises.

Most small-scale farmers in the Sub-Saharan region are struggling to meet optimum yields. This is due to their inability to afford chemical fertilisers and lack of knowledge on sustainable agricultural practices, e.g. water and nutrient management. Research and innovation on sustainable or best agricultural practices is important in transformative research introducing HEDFs as part of the input supply across the food value chain. In this regard, studies were done to assess the application of best agricultural practices on the use of HEDFs in accordance with local farmers production systems identified during participatory activities. Three case studies were done at Bishopstowe Agricultural Living Lab (BALL), University of KwaZulu-Natal and Appelsbosch. Seedlings were produced using DEWATS effluent from Newlands Mashu and co-compost from one of RUNRES innovations. The effects application of human excreta derived materials under dryland agriculture and impacts on crop yield and soil health was done at BALL. The co-compost was tested as a growing media at Appelsbosch church farm. Biophysical site assessment was done at BALL. Results showed that the BALL is characterised of clay soils, moderately susceptible to erosion and receives adequate rainfall to support chilli pepper production. A dryland experiment was done using five treatments (chicken manure, co-compost + urine, urine, conventional fertiliser and no fertiliser) and four replicates. Data was collected on crop yield, soil health and potential groundwater contamination. The results showed that the yields of chilli peppers were comparable in all treatments. Most aspects of soil health; microbial communities, enzymatic activity and soil chemical analyses did not significantly differ in all treatments except for microbial activity, organic C and extractable P. Microbial activity was significantly higher in chicken manure amendments. The organic C and extractable P significantly increased in co-compost. The extractable P was higher in both co-compost and chicken manure. There were no pathogens and mineral nutrients (N and P) observed in analysed water samples meaning that the groundwater was not contaminated. Meaning that short term application of co-compost under dryland conditions increased soil P without significantly altering soil microbial activity.

High agricultural input costs are one of the identified challenges being faced by small scale farmers and this limits their production. This together with the dilemma of managing wastewater in different seasons and the lack of co-compost markets led to the study that assessed the potential use of treated domestic wastewater and co-compost for vegetable seedling production. A study was done in a complete randomised design with three irrigation water sources (municipal tap water vs horizontal flow constructed wetlands effluent vs anaerobic filter effluent); two growing media (sewage sludge derived co-compost vs conventional growing media) and three crop types (Swiss chard, tomato and onion). Data was collected on seedling emergence, seedling vigour, plant pathogen contamination (growing media and seedlings) and pathogen transfer rate. The seedling vigour increased in co-

compost media irrigated with DEWATS effluent. All the treatments including conventional seedling production practices did not meet the Fertilisers, Farm Feeds, Agricultural remedies and Stock remedies Act no 36 of 1947 requirements for a good growing media in terms of supporting 80% germination except for Swiss chard. However, all the treatments were above the minimum standards (>50%) for an ideal growing media as all supported at least 60% germination. *Phytopythium spp.* were found in all growing media treatments. *Fusarium spp.* were detected in all irrigation treatments. Therefore, integrated plant disease management practices including disinfection of irrigation water and hygienic handling of growing media prior to use needs to be considered. The use of co-compost and DEWATS effluent complied with the Occupational Health and Safety Act of 1993 that there were no health hazardous traces of *E. coli* on seedlings to expose farmworkers during handling.

The use of co-compost as a growing media in intensive crop production provide an opportunity to diversify its use. Co-compost and seedlings were provided to the farmers in Appelsbosch. The farmers used the co-compost to grow tomatoes and chillies. The project team collected and analysed the yield data. Tomato grown in coco peat had significantly higher yield ($P<0.05$) compared to co-compost. The reasons behind the results were not clear. A separate study was done to test whether the co-compost was phytotoxic as a growing media. A factorial design was laid out as two soil types x four fertiliser types and four replicates. The treatments were co-compost alone, chemical fertiliser, co-compost + chemical fertilizer and the control (zero fertiliser) and maize was used as a test crop. The co-compost significantly increased all the growth parameters of maize especially in sandy soils applied fertiliser. Further discussions were done with farmers to understand why co-compost failed to support chilli and tomato production. The only information obtained was that the crops failed due to a disease outbreak. Thus poor tomato and chilli growth was not attributed to co-compost. Pest and disease management is one of the problems likely to affect small scale farmers who do not have adequate financial capacity to purchase agrochemicals and labour. This is exacerbated by the fact that they do not have access to micro loans due to lack of compliance. In this regard, education and guidance on agribusiness management skills such as compliance in business environment is required.

Most CBE studies focus on technology improvement giving little attention to the adoption and utilisation of innovations that improve livelihoods. A sustainable approach that improves economic viability across the food value chain is needed. Integrating agro-processing as a component of the sanitation value chain linked to food systems may promote sustainable resource recovery and reuse while improving livelihoods. A mixed methods study was done to assess the extent to which agro-processing can be incorporated as an integral component of the sanitation value chain by closing a loop across the food value chain while adding value to enhance sustainability of the circular sanitation bioeconomy. The study further co-proposed value addition options for food crops. Key informant interviews, focus group discussions, literature review and participatory informed laboratory experiments were conducted. Crops selected during the focus group discussions with farmers and consultations with stakeholders were chillies, onions, cabbages, Swiss chard, carrots, beetroot, maize, dry bean and potato. Processing options were maize processing (samp, instant porridge, soup, fresh maize and stock feed), dry bean mixed with samp, potato processing (fried chips and baby food), vegetables (mixing carrots, green beans and baby corn) chopping and packaging of Swiss chard, onions and cabbages. Some opportunities for agro-processing include the use of agricultural products (e.g. traditional chicken and vegetable chutney) for restaurants as is done in the local culture. The study co-identified stakeholders needed to propel the agro-processing agenda, starting from the farming systems, post-harvest handling and marketing. The interaction of these stakeholders and partners is crucial for a sustainable agro-processing business. The research institutions play a role in moderating transdisciplinary activities. Machinery optimisation (e.g. energy efficiency), agro-processing product quality assurance for consumer protection and satisfaction and compliance are very crucial in linking agro-processing with circular bioeconomy. A study was done to assess the postharvest handling and processing technologies such as blanching and solar drying of chillies. The study investigated the effect of blanching chillies from five treatments (urine + co-compost vs urine vs chicken manure vs conventional fertiliser application vs no fertilizer applied) on chilli nutrition (ascorbic acid) and appearance for customer satisfaction (colour saturation). Other study compared the effect of beforementioned five fertiliser treatments and two harvesting behaviours (harvesting directly on the plants vs picking on the ground) on microbial (*E. coil*) contamination. The study revealed that blanching chillies reduces ascorbic acid losses, increases energy use efficiency and maintains colour saturation during drying for best appearance. Plants produced using co-compost and urine were safe to consume since the *E. coli* levels on the chillies were below limits of 20 MPN/g. Therefore, simple technologies which are solar powered may be conducive but more studies are needed in technological optimisation.

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AF	: Anaerobic Filter
BFR	: Brominated Flame Retardants
BOD	: Biological Oxygen Demand
BSFL	: Black Soldier Fly Larvae
CAB	: Community Ablution Blocks
CBE	: Circular Bioeconomy
CEC	: Contaminants of emerging concern
CGCSA	: Consumer Goods Council of South Africa
COD	: Chemical Oxygen Demand
DALRRD	: Department of Land Reform and Rural Development
DEWATS	: Decentralised Wastewater Treatment System
DFFE	: Department of Forestry Fisheries and the Environment
DOH	: Department of Health
DOM	: Dissolved Organic Matter
DTIC	: Department of Trade Industry and Competition
DWS	: Department of Water and Sanitation
DWYPD	: Department of Women Youth and People with Disabilities
EU	: European Union
FFSR	: Fertilizers, Farm Feeds, Seeds and Remedies Act 36 of 1947
FGD	: Focus Group Discussion
GGAP	: Global Good Agricultural Practices
HEDFs	: Human Excreta Derived Fertilisers
HFCW	: Horizontal Flow Constructed Wetlands
LaDePa	: Latrine Dehydration Pasteurisation

NEMA : National Environmental Management

NUC : Nitrified Urine Concentrate

NWA : National Water Act

PAR : Participatory Action Research

PCC : Population Concept Context

PPE : Personal Protective Equipment

PRA : Participatory Rural Appraisals

PRISMA : Preferred Reporting Items for Systematic reviews and Metanalysis (PRISMA)

PYD : Pythium-selective medium

RUNRES : Rural Urban Nexus: Establishing a nutrient loop to improve city region food systems

SABS : South African Bureau of Standards

SMMEs : Small Medium Microenterprises

SSP : Sanitation Safety Planning

UDDT : Urine Diversion Dehydrated Toilets

USEPA : United States Environmental Protection Agency

VFCW : Vertical Flow Constructed Wetlands

VIP : Ventilated Improved Pit latrine

WHO : World Health Organisation

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1 GENERAL INTRODUCTION

1.1 Background

The current global food systems are not sustainable, characterised by continuous natural resource extraction and excessive waste generation at the end point of the value chain. Linear food system flows exert pressure on natural resources and their capacity to sustain future generations while accelerating environmental disintegration as well as contributing to global challenges such as biodiversity loss, climate change and social illnesses (Moya et al., 2019b). South African statistics shows that 64% of the population has access to flushing toilets while 32% are using improved and unimproved pit latrines StatsSA (2021). However, with continuous urbanisation, local authorities are failing to cope up with providing urban sanitation services. On the other hand, faecal sludge management from onsite sanitation systems remain a challenge in South Africa and most developing countries (Muoghalu et al., 2023). Poor sanitation systems have been widely blamed as major contributors to global burden of diseases as well as environmental pollution due to discharge of untreated wastewater into water bodies (Prüss-Ustün et al., 2019). A sustainable approach to address sanitation and food insecurity issues is in a closed loop circular bioeconomy is urgently needed.

A closed loop circular bioeconomy associated with recovery and reuse of natural resources is a well proven concept to protect the environment while improving food systems. Transitioning from conventional linear paradigms requires a transdisciplinary and multilateral approaches rather than acting in silos (Genovese et al., 2023; Smith et al., 2023). Thus, mobilising all sustainability instruments such as appropriate technologies, best practices, social acceptance, health and safety tools, economic and financial viability approaches as well as stimulating enabling policy, legal and regulatory environment across the food and waste value chains. This can be done at different scales; local, national, regional and international levels. The World Health Organisation has developed guidelines that allow safe utilisation of sludge and urine/urine products in agriculture (WHO, 2016); and in South Africa, policies and regulations that allow the use of human excreta derived materials in agriculture are in place. Local authorities such as eThekwini municipality in KwaZulu-Natal together with key stakeholders such as the Water Research Commission (WRC) have been very progressive, working with the University of KwaZulu-Natal, Pollution Group and Crop Science on integrating sanitation and agriculture (Odindo et al., 2022a). However, most of this work was experimental and limited to pilot scale. It will be important to consider barriers to transformative change that limit the wider adoption and scaling out of these technologies. Potential barriers to transformative change include but are not limited to health and safety, environmental concerns, social acceptance and perception, the legal and policy framework, costs and long-term economic viability. Concerns have been raised regarding pathogens and in recent times, emerging chemicals of environmental concern (micropollutants} such as pharmaceuticals and other personal care products (Necibi et al., 2021; Sekabira et al., 2022; WHO, 2006). These include pharmaceuticals and chemicals of environmental concern, whose impacts on soils, crops, environment, human beings and subsequent transfer into the food chain are not well understood. Initiatives aimed towards upscaling from experimental conditions and pilot phases will require engaging with all stakeholders involved in the value chain, particularly farming, processing, transportation, waste recycling, including municipal authorities, government and policymakers. Similarly, processes that could eliminate pathogens and the negative impacts of chemicals or environmental concern on food production and the environment require testing new technologies such as activated carbon from pyrolysis of human faecal sludge and ultraviolet (UV) light and ozonation treatment (Gomes et al., 2013; Nkomo et al., 2021; Udert et al., 2016).

The concept of transformation refers to "*a fundamental qualitative change that often involves a shift in paradigm and may include variations in perception and meaning, changes in underlying norms and values, reconfiguration of social networks and patterns of interaction, changes in power structures, and the introduction of new institutional arrangements and regulatory frameworks*" (Field et al., 2012). Transformative approaches are needed to change the way nutrient recovery from wastewater and human excreta is perceived as an addition to sanitation technologies for sustainable waste management. This has a potential to create new pathways for long-term food, soil and nutrient security, while simultaneously, provide sustainable solutions to the waste management challenges in unplanned densely populated urban and peri-urban settlements, which are not connected to centralized sewage systems. Transformational approaches in reframing human excreta as integral components of farming and food systems should be integrative and adaptive and allow novel partnerships, cross sectoral and multi-stakeholder relationships when designing, adapting and scaling up innovative sanitation technologies that allow nutrient recycling. This integrative and adaptive component has often been absent in most research initiatives being undertaken on nutrient recovery and reuse in agriculture.

1.2 Aims and objectives

- To assess local community attitudes, perceptions, and barriers (legal and economic costs) towards the use of waste-based fertiliser products for crop production.
- To apply advanced waste treatment methods in human wastes such as excreta materials and activated sludge, monitoring and evaluating the availability of micropollutants and pathogens, and their subsequent prevalence in soils and possible transfer into plant tissues.

- To recover bioresources such as struvite (fertilizer) and biosolids from the human wastes such as excreta materials and activated sludge.
- To grow selected crops to test the fertiliser value of the waste-based bioresource products, impacts on soils, crops, and the environment.
- To propose small-scale processes for value addition of locally produced crops using the recovered waste-based bioresource products.

1.3 Methodological framework

The general methodological framework showing the outline of the report is summarised in Figure 1.1.

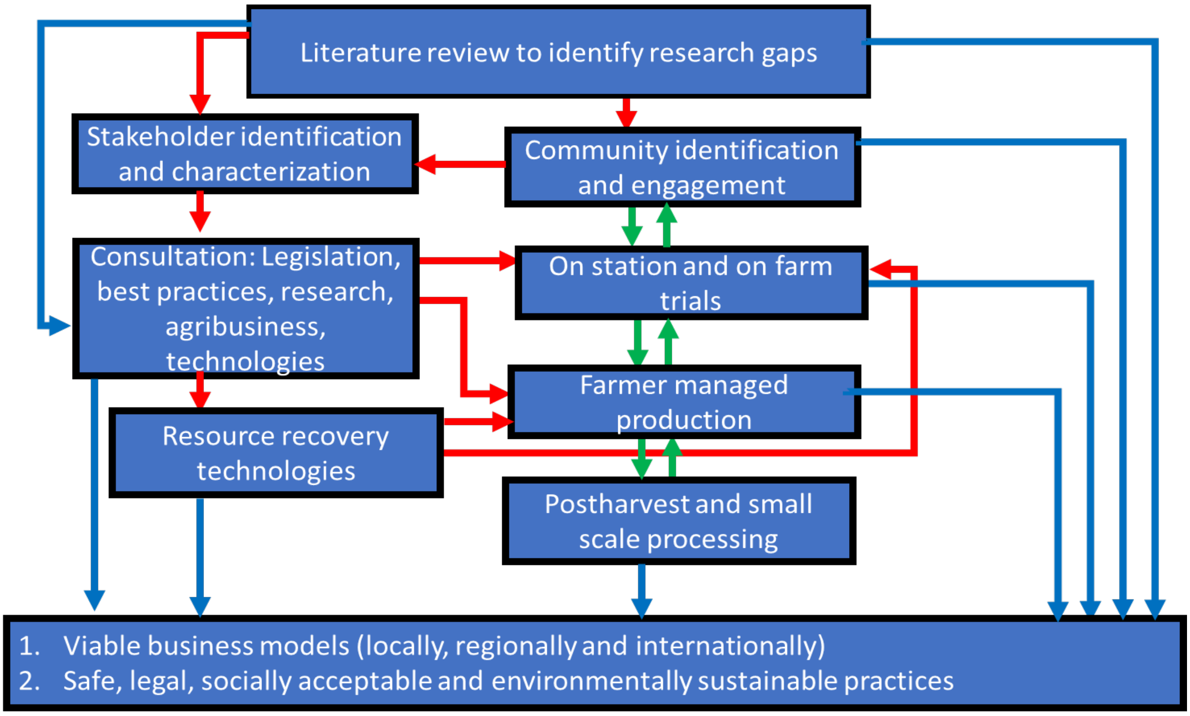

Figure 1.1. General methodological framework showing the outline of the report.

Chapter 1: Introduction

This section introduced the background of the study, justification and provide an outline of the final report.

Chapter 2: Literature review

A critical review was done to discuss the extent to which available onsite sanitation related technologies for resource recovery can be linked with South African food systems. The study explained the transformative research approach. The barriers and opportunities that may support or impede transitioning from linear material flows sanitation systems to closed loop circular systems were critically discussed. The literature guided the roadway for the project through identification of best approaches to successfully transform existing food systems at a local level, it further provided recommendations for scaling to national, regional and international levels. The missing research gaps were identified and included in the preceding research.

Chapter 3: Social context studies: stakeholder mapping, characterisation and engagement

This section reports on study contextualisation, identification and characterisation of stakeholders in alignment with the project vision. The communities and study boundary were clearly defined and mapped. The communities were engaged, challenges faced within their food systems were identified and discussed. The stakeholders that may address the challenges identified by farmers through finance, technological support, research and legal structures were identified, characterised and engaged.

Chapter 4: Advanced treatment technologies

This section focused on identifying advanced and simple wastewater treatment technologies with DEWATS for unrestricted agricultural use. The lab scale treatment of wastewater using ozonolysis was done to increase the DEWATS effluent quality for unrestricted agricultural use.

Chapter 5: Bioresources recovery: urine-based products recovery and co-compost fortification

The section reports on the treatment of urine into fertilisers such as struvite and subsequent fortification of the co-compost as a high value organic amendment. The compliance of the resulting fertiliser products with the South African Fertilizers, Farm Feeds, Seeds and Remedies Act 36 of 1947 (FFFSR) was assessed.

Chapter 6: Sustainable practices: agricultural trials

The section reports on the application of best agricultural practices emanating from WRC K5/2777 practical guideline on agricultural use of human excreta derived materials. The section reports on identification of target study crops for small scale processing, on station trials (participatory and researcher managed trials) and on farm trials were conducted to test the fertiliser value of HEDFs.

Chapter 7: Small scale processing and value addition

The section used information on experimental trials, stakeholder consultation, literature review, resource recovery technologies community members consultation and experimental post harvesting technologies to propose small scale options for value addition.

Chapter 8: Recommendations for safe, legally, socially acceptable and environmentally sustainable human excreta recovery and reuse practices.

The section summarises and concludes the overall findings based on four main objectives of the study.

2 TRANSFORMATIVE APPROACHES IN TRANSITIONING TO A CIRCULAR BIOECONOMY IN SOUTH AFRICA: A SCOPING REVIEW

2.1 Introduction

The world population has been increasing unprecedently and this is expected to continue. According to Hussain and Bhat (2018) the world population was 7 billion in 2018 and this has been predicted to reach 9.1 billion by 2050. Thus, increasing the demand for food, social services, sanitation, resource extraction and the amount of waste generated. A scrutiny into the global sanitation status shows that an estimated 2.3 billion people still lack access to improved sanitation (Koné et al., 2019). To those with access to sanitation, 2.7 billion are depending on onsite systems (Chandana and Rao, 2022; Koné et al., 2019). Onsite sanitation systems are predominantly used in developing countries, and their usage is expected to increase due to prohibitive establishment and maintenance costs of centralised sanitation systems (Koné et al., 2019). A household survey conducted in South Africa shows that about 30.1% of households are using pit latrines (improved or unimproved), 63.7% have flushing toilets and only 0.1% use ecological sanitation (ecosan) toilets (StatsSA, 2021). The use of pit latrines is also common in various developing countries around the globe (Chandana and Rao, 2022; Guo et al., 2021; Kalulu et al., 2021). Pit latrines are rarely emptied and, in most cases, if emptied the faecal sludge is unsafely disposed into the environment (Chandana and Rao, 2022; Jenkins et al., 2015). As a result, contaminated boreholes have been reported in the Sub-Saharan region, leading to outbreaks of enteric diseases (Mamera et al., 2021; Masindi and Foteinis, 2021; Ngasala et al., 2021). Safe collection, treatment, and valorisation of human excreta prior to reuse should be given immediate attention.

Most developing countries, especially in the Sub Saharan Africa, for example South Africa, are burdened by socio-economic challenges such as food insecurity, increasing costs of goods and services, unemployment (Chakona and Shackleton, 2019) and poor soil fertility (Tindwa et al., 2019). Continuous loss in soil fertility is attributed to nutrient mining; the loss of nutrients from agricultural soils as harvestable crop products, across the food value chain as food wastes and human excreta after consumption, without replenishment in the soil (Tindwa et al., 2019). This is worsened by minimal use of organic fertilisers, triggering multiplier soil health problems such as soil biodiversity loss and its ability to effectively retain water and nutrients as well as reduced fertiliser use efficiency (Amoah et al., 2017). Sustainable circular systems to capture nutrients from the food value chains as food waste and human excreta and bring them back to the soil double solve sanitation and food security challenges (Cofie et al., 2016; Rosemarin et al., 2020; WWAP, 2017).

There is a paradigm shift in attitudes and perceptions towards handling human excreta as it is treated as a “resource” not “waste” (Koné et al., 2019; Odey et al., 2017; Rosemarin et al., 2020; Simha et al., 2020). The “toilet revolution” and the ecological sanitation (ecosan) concepts are both aligned with sanitation systems that are environmentally, economically and socially sound for safe containment, handling, treatment, valorisation and agricultural use of human excreta products. Several technologies to recover agricultural resources (human excreta derived fertilisers; HEDFs) from human excreta have been commissioned, evaluated and some are or yet to be commercialised. These technologies are used to produce faecal sludge derived products (Cofie et al., 2016; Harrison and Wilson, 2012; Nkomo et al., 2021; Septien et al., 2018), urine derived products (Etter et al., 2015; Udert et al., 2016) and decentralised wastewater treatment system (DEWATS) effluent (Arumugam and Buckley, 2020; Gutterer et al., 2009; Reynaud and Buckley, 2015).

The use of HEDFs have been evidenced to improve soil health (Andersson, 2015; Fuhrmann et al., 2022; Mamera et al., 2021). Studies on social perceptions and attitudes towards the use of HEDFs are widely documented and guidelines to minimise associated risks are available at international (USEPA, 2012; WHO, 2006, 2016) and local level (du Plessis et al., 2017; DWS, 1996; Snyman et al., 2006; Tesfamariam et al., 2020). A comprehensive South African context practical guideline on safe, economically viable, environmentally benign and socially acceptable utilisation of various human excreta derived fertilisers was established (Odindo et al., 2022b). The applicability of the practical guidelines is yet to be validated in complex local communities. Therefore, this review aims to highlight the extent to which transformative approaches may be applied to facilitate transition from traditional unsustainable linear materials flow to circular bioeconomy. The circular bioeconomy model has a component of agricultural end-use along the sanitation value chain. The review further discusses potential barriers that might impede transformative approaches in integration of sanitation-based fertilisers for sustainable agriculture in South African communities and beyond. The review identifies and provides strategies to the implementation of transformative approaches in stimulating linkages between onsite sanitation and food systems, in addition to gaps for further research.

2.2 Methods

The study provides evidence for current opportunities in the implementation of sustainable sanitation linked to food systems in South African context and identify gaps for further research. Therefore, a scoping review approach is employed according to the methods described by Arksey and O'Malley (2005) and modified by Peters et al. (2020) as shown in Table 2.1.

Table 2.1: Modification of Arksey and O'Malley (2005) traditional scoping review methods by Peters *et al.* (2020)

Step	Arksey and O'Malley (2005)	Peters et al. (2020)
1.	Identifying the research questions	Defining and aligning the objective and question
2.	Identification of relevant studies	Developing and aligning the inclusion criteria with the objective and question
3.	Selection of studies	Describing the planned approach to evidence searching, selection
4.	Data charting	Searching the evidence
5.	Collating, summarizing and reporting the results	Selecting the evidence
6.	Consultation is optional	Extracting the evidence
7.	N/A	Charting the evidence
8.	N/A	Summarizing the evidence in relation to the objectives and questions

The definition and alignment of objectives and question has been carried out according to the Preferred Reporting Items for Systematic Reviews and Meta-Analysis criteria for scoping reviews (PRISMA-Scr) guide (Peters et al., 2020). The Population Concept Context (PCC) framework was used to frame research questions based on the topic in question and the specific objectives of the review, and this informed the inclusion criteria. There was no specific targeted population group (e.g. age, gender or race), hence the review only focuses on the concepts and context of the subject. The review concepts are centred towards addressing barriers that might impede the application of transformative approaches in transitioning to a circular bioeconomy, linking sanitation with agriculture in food systems. The review focuses on the South African context, although global examples are also provided where appropriate. Research questions were formulated as follows:

- To what extent are the South African technological advancements, policy and legal frameworks supportive of human excreta recycling initiatives?
- What are the social dynamics, human health, environmental and economic barriers prohibiting the transitioning to a circular sanitation bioeconomy linking sanitation to food systems in South African communities?
- What are the strategies to facilitate transformative approaches in successful implementation of circular bioeconomy models linking sanitation with food systems in South African communities?

A comprehensive and unbiased search strategy required by the JBI scoping reviews protocols was implemented. All the published peer reviewed literature was gathered from two academic databases namely Web of Science and Scopus. Grey literature was included during the review to increase comprehensiveness and provide a balanced picture of the subject matter. Some of the randomly selected relevant literature that could not be identified from the search engine was also included. The topic search which includes the title, abstract, keywords is summarised in Table 2.2.

Table 2.2: The search strategy including main terms used for the scoping review in web of science and Scopus databases.

Key area	Main term	Web of Science	Scopus
Concepts	**Problems:** Unsustainable sanitation and Nutrient mining **Solutions/Interventions:** Transformative research and Resource recovery from sanitation systems and reuse **Barriers:** Social dynamics, Environmental risks, Health risks, Economic viability, Policy, legal and institutional framework **Outcome:** Sustainable sanitation and Circular economy	"nutrient mining" or “Institutional issues” or “legal framework” or "attitudes" or “social perceptions” or "environment" or “environmental risks” or “economic viability” or "viability" or “health risks” AND "Department of Water and Sanitation" or "DWAF" or human excreta guideline” or "food systems" or "Ecosan" or “human excreta derived fertilizers” or "human excreta derived materials" or urine or struvite or “ABR effluent” or DEWATS or ABR or biochar or black soldier fly larva or co-compost or “nitrified urine” or “faecal sludge” or “treated wastewater” or "sludge application rate advisor" AND “Sustainable agriculture” or “circular economy” or “resource recovery” or “agriculture” or “reuse in agriculture”	"Nutrient mining” or “Institutional issues” or “legal framework” or “attitudes” or “social perceptions" or "environment" or "environmental risks" or "economic viability" or "viability" or "health risks" AND "Ecosan” or “human excreta derived fertilizers” or “human excreta derived materials” or urine or struvite or "ABR effluent" or DEWATS or ABR or biochar or residue or co-compost or "nitrified urine" or "faecal sludge" or "treated wastewater" or "sludge application rate advisor" AND "Circular economy" or "resource recovery" or "reuse in agriculture" AND Sanitation

Key area	Main term	Web of Science	Scopus
Context	Low-income communities of South Africa	“Low income” or “South Africa” or “developing countries” or “Sub Saharan” or “Africa” or “Rural” or “Peri-urban” or “Urban”	“Low income” or “South Africa”

The screening criteria was established and discussed amongst different co-authors. The records included during the study are reported by the Preferred Reporting Items for Systematic reviews and Metanalysis (PRISMA) flow chart. The studies identified through database search were combined with studies from other sources (grey literature) and transferred into the endnote bibliography, where duplicates were removed. The identified records were further screened for irrelevant topic and abstract. The exclusion criteria were based on language, time frame and key words. Full texts were obtained from unrestricted access articles, those that could not be found were either discarded or requested from the librarian. The included records were used for evidence extraction, synthesis and while some were identified with the assistance of librarian. The remaining records were screened for eligibility, with the exclusion of those with non-relevant content. The included records were used to synthesise evidence based on six major categories of concern in sustainability science: technological capacity, best practices, health and safety, social perceptions, economic and financial viability and institutional, policy and legal framework.

2.3 Results and discussion

The PRISMA flow chat for the literature review is shown in Figure 2.1. A total of 512 records were identified from the Scopus and Web of Science. The 225 duplicated records were removed using endnote. To increase the breadth of enquiry, twenty-five grey literature records were included from non-profit organizations. All the remaining 218 records were subjected to initial screening based on title, keywords and abstract. From the total fifty-eight records included during screening, some other studies were then picked up randomly from references of selected articles and other random Google Scholar searches.

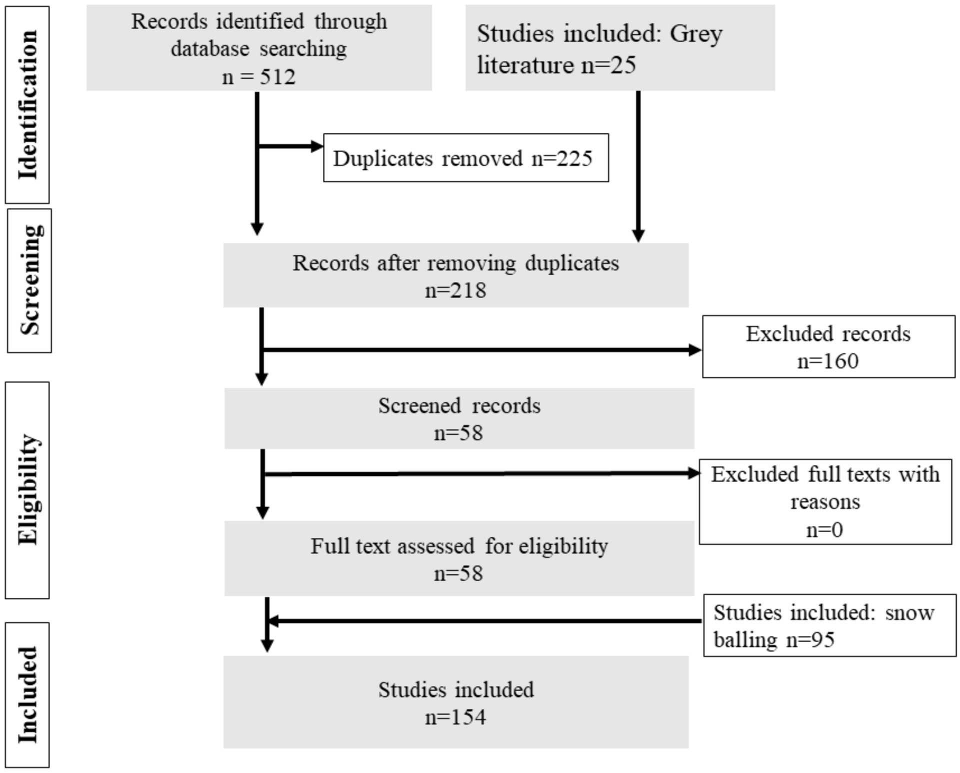

Figure 2.1: The Preferred Reporting Items for Systematic reviews and Metanalysis (PRISMA) flow chart for mapping records identified, excluded and included during the scoping review process (Peters et al., 2020).

All the reviewed articles increased from 1995 to 2023 (Figure 2.2). The increase in publications shows a major increase in research towards transformative approaches in transitioning towards a circular economy. The study focused on South African context, providing examples of regional and global case studies. Therefore, a total of 53 records (one third) was from South Africa, followed by India (n=10), Ghana (n=9) and Kenya (n=3), which are all within the global South. However, a link with the global North was evidenced by articles reviewed from China (n=4), USA (n=4) and various European countries (each n=1) (Figure 2.2).

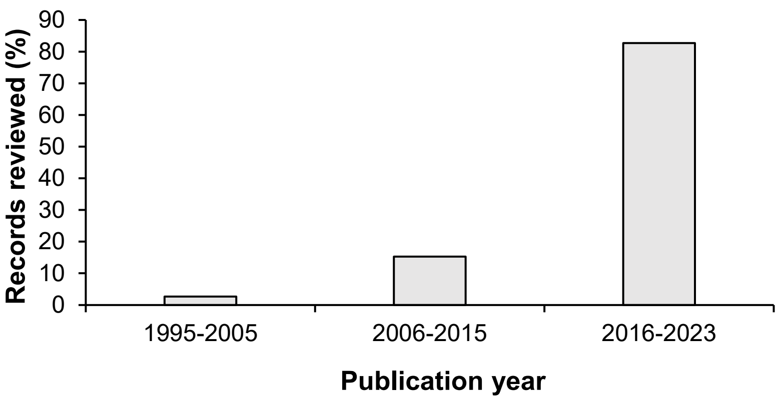

Figure 2.2: The number of records included in the study per each 10-year interval since 1995 to 2023.

Articles were categorised into six thematic areas namely, on technological capacity (n=48), best practices (n=34), health and safety (n=14), social perceptions (n=17), economic and financial viability (n=7) and legal and policy issues (n=20) (Figure 2.3). This shows that more focus was orientated towards technological developments, social perceptions, best practices and legal and policy issues with little attention on economic viability.

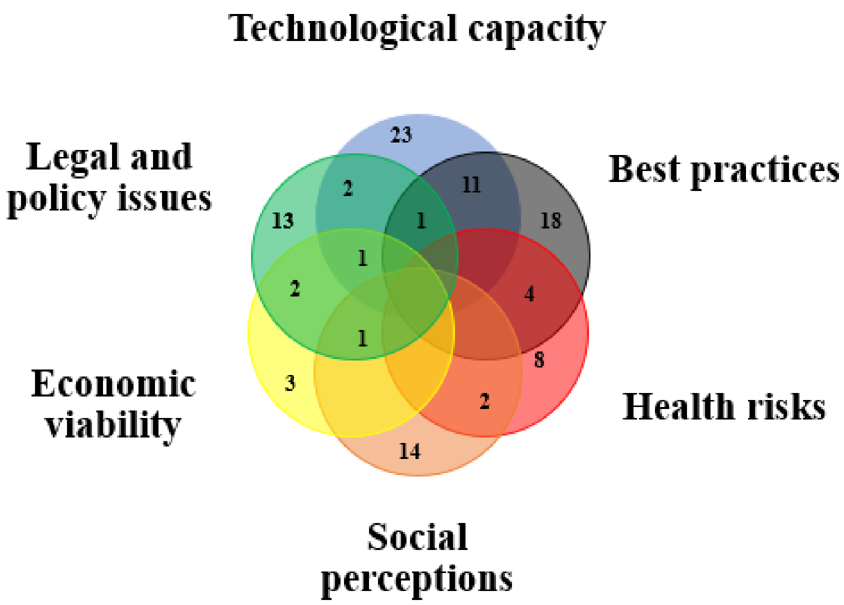

Figure 2.3: Venn diagram showing relationships amongst different records identified and used for evidence synthesis based on six thematic areas.

The articles reviewed per geographical location are shown in Figure 2.4. The study focused on South Africa context in comparison with other developing and developed countries. Hence, fifty-three articles included are from South Africa. Some included articles are from the Asian countries such as India (n=10) and China (n=4) and African countries such as Nigeria (n=9), Kenya (n=3) and Uganda (n=3). The rest of the articles are from countries in South America, Europe, Australia (n=1) and North America (n=2).

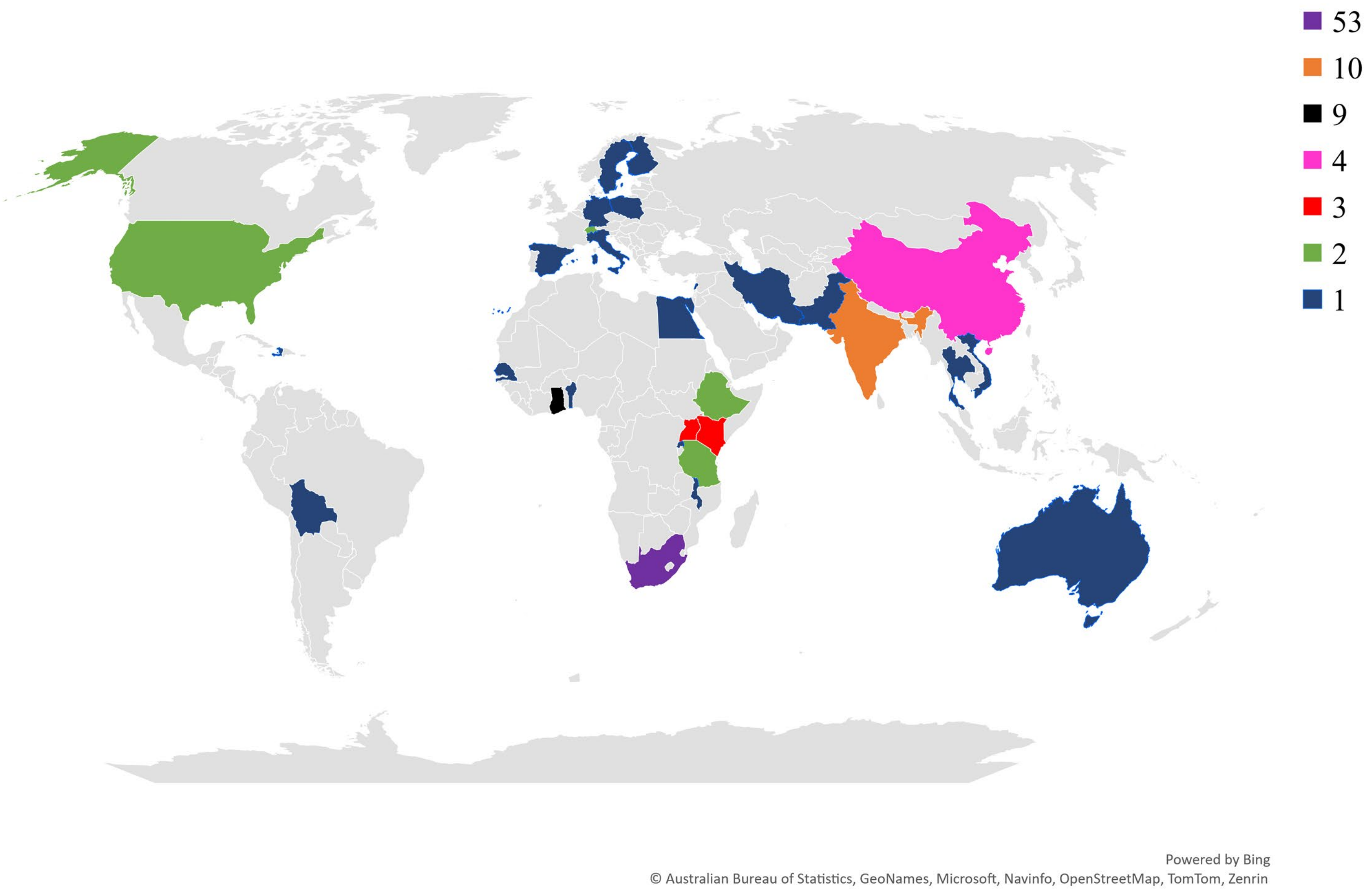

Figure 2.4: The map showing number of articles reviewed per geographical location.

2.4 Transitioning towards a circular economy

The circular economy concept is a way of understanding implementation of waste management hierarchy and how it contributes to the green economy, by detaching the economic activities from harmful environment (DFFE, 2020a). The concept was initially explained by David Peace and R. Kerry Tuner in 1990 as a principle that attempts to join in the energy and resources cycling principles of natural systems into artificial systems (Gwynn-Jones et al., 2018). This involves mimicking natural systems by establishing a link between primary manufacturing resources with waste, thereby closing a loop from extraction of new natural resources as raw materials for production and concurrently minimising waste generation. It incorporates the R strategies such as “Reduce” “Reuse” “Recycle” “Regenerate” meaning, reuse what is reusable or recycle what is not reusable. Noble (2018) described a circular economy as an approach that promote efficient use of resources through life cycle way of thinking and create markets for waste and residual materials. Thus, connecting cities and farms while closing loops.

Dubois and Gomez San Juan (2016) defined the bioeconomy as, “a knowledge-based production and utilisation of biological resources, principles and processes to sustainably provide goods and services across all economic sectors”. Although Dubois and Gomez San Juan (2016) considered bioresources as primary agricultural raw materials and agricultural wastes, in this review the focus is centred towards human excreta, although linkages with municipal solid waste is also considered. The circular bioeconomy idea applies to sanitation systems where resources such as nutrients, carbon and water extracted during agricultural production can be recovered from human excreta after consumption and reused again for food production (Saab et al., 2022). This minimises loss of even non-renewable resources like phosphorus. The circular bioeconomy can be applied in ecological sanitation (ecosan) approach which is a sustainable way of establishing closed material flow loops from sanitation systems to agriculture (Figure 2.5). Bekchanov and Gondhalekar (2022) estimated a global cost of USD$ 222.9 billion resulting from poor sanitation and wastewater treatment. Taking into consideration the occurrence of SARS-CoV-2 virus in human excreta (Guo et al., 2021) and the impacts it has on global food systems, circular bioeconomy models that allow excreta treatment and reuse improve livelihoods by reducing health costs.

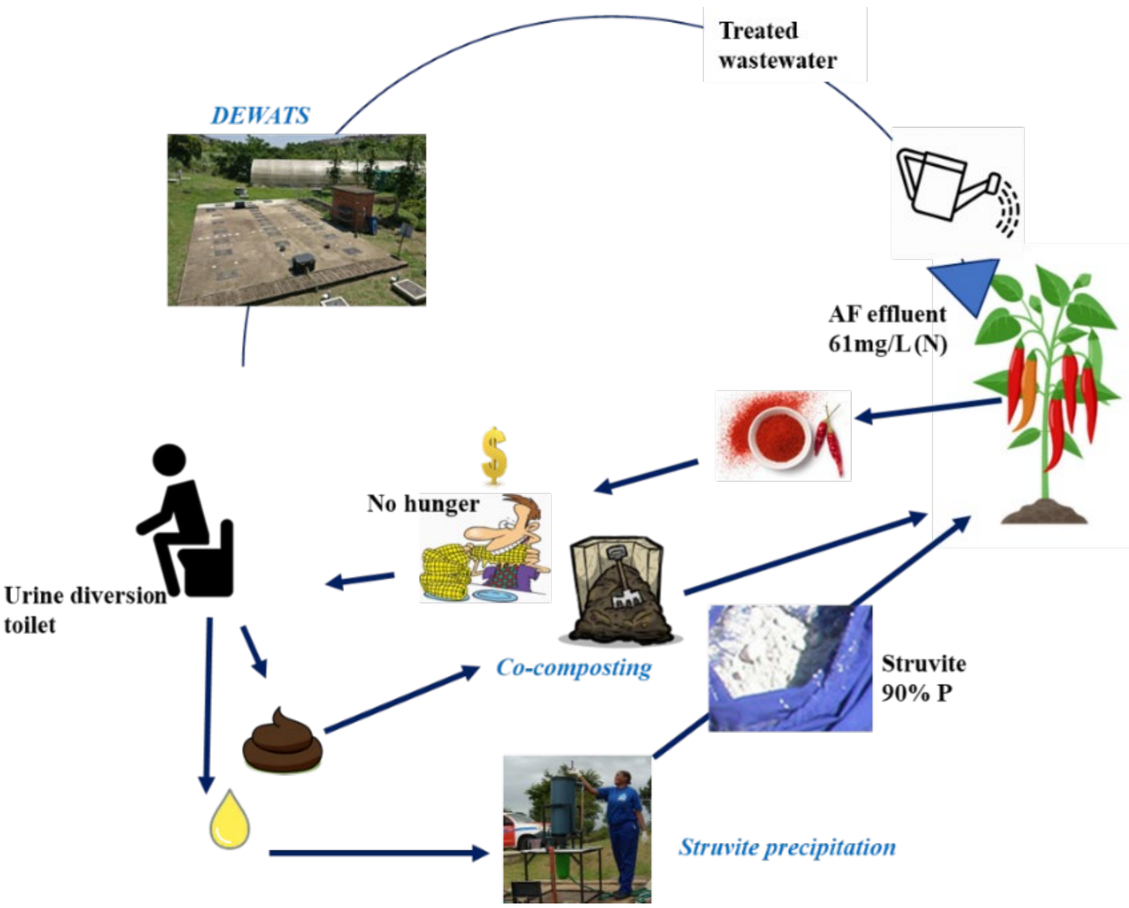

Figure 2.5: Envisioned circular bioeconomy linking sanitation with sustainable food systems in South Africa.

Transitioning to a circular bioeconomy has been described as a process on structural changes informed by introduction of transformative eco-innovation (de Jesus et al., 2021). According to OECD (2009) eco-innovation is defined as "*the development of products, processes, marketing methods, organisational structure and new or improved institutional arrangements, which, or not, contribute to a reduction of environmental impact in comparison with alternative practices*". Lindahl and Dalhammar (2022) suggested that we need to change the way we perceive products, markets, ownership and resources from a linear economy view to a circular bioeconomy perspective. The transition is a complex process which take into consideration socio-economic issues, policy and regulation, technology and innovation, and include all sustainability dimensions such as energy efficiency, food security among others (Table 2.3). Thus, the transition to a circular bioeconomy is propelled by availability of socially acceptable, legal, environmentally sustainable technologies and enabling policies (Moya et al., 2019b; Odey et al., 2017; State of Green, 2021). A comprehensive study done by Rezaie et al. (2022) concluded that transdisciplinary collaborations involving multistakeholder across value chains, communities, academia and governmental institutions is needed to spearhead the transition process.

Table 2.3: Summarised issues of consideration to drive the transition to a circular economy through transformative research approaches.

Issue of consideration	Actionable areas	Source
Circular economy impacts	Assessing environmental sustainability, e.g. lifecycle analysis, material flows and impact of recycling processes. Economic development, e.g. mapping economic returns to communities, contribution to GDP through circular economy activities. Understanding the transition process in different contexts, e.g. understanding disconnections between global supply and value chains, linkages between circular economy with other sustainability themes such as climate resilience, biodiversity, adaptations, resource security and global pandemics including conflicts.	Rezaie et al. (2022); de Jesus et al. (2021); Otoo et al. (2016); Melati et al. (2021); Enhance Project (2021); Lindahl and Dalhammar (2022)
Just transition	Involvement of civil societies in identification of advantaged and disadvantaged groups. Addressing inequalities from resources conflicts and conflicting interests. Social inclusion and equity, e.g. gender roles, human rights and roles of marginalised people. Managing power dynamics and decision making in supply chains and financial systems, e.g. global waste trade regulations, gender dominance.	Taron et al. (2021); Khalid et al. (2018).
Viable business models	Feasibility studies on viable markets to support profitable investments in circular economy approaches, e.g. value addition. Involvement of Small, Medium and Micro enterprises (SMMEs) and other entrepreneurs to fast track the transition. Capacities of different stakeholders or actors to implement CE strategies and opportunities for partnerships.	Otoo et al. (2018); Rezaie et al. (2022); Otoo et al. (2016); Noble (2018); Lindahl and Dalhammar (2022)

Issue of consideration	Actionable areas	Source
Social perceptions (every actor across the value chain)	Piloting circular economy practices and establishing a scaling up strategy. Understanding consumer perceptions and attitudes towards circular bioeconomy-based products and how to influence behavioural change (e.g. willingness to use or pay for the circular economy product). Availability, affordability and accessibility of more sustainable products and how these can be linked to equity. Implementation of higher R strategies such as refusing and reducing consumption.	Rezaie et al. (2022); López-Serrano et al. (2022); Water and Sanitation Program (WSP) and (IWMI) (2016); Zhou et al. (2022); Guo et al. (2021); Ignacio et al. (2018); Keraita and Drechsel (2015); Nansubuga et al. (2016); Ricart and Rico (2019); Wells et al. (2016); Lindahl and Dalhammar (2022); Gwara et al. (2023)
Technology	Identification, improvement and designing of energy efficient technologies to recover resources from waste. Feasibility studies on chemical and mechanical recycling processes for commercial use. Innovative approaches to integrate circular bioeconomy principles into value chains. Assessment of technology readiness level.	Rezaie et al. (2022); Cofie et al. (2016); Singh (2021); Musazura and Odindo (2021); Montwedi et al. (2021); Kesari et al. (2021); Singh (2021); Musazura and Odindo (2021); Montwedi et al. (2021); Kesari et al. (2021); Keraita et al. (2014); Lautze et al. (2014); Nansubuga et al. (2016); Ricart and Rico (2019); Russo et al. (2019); Odey et al. (2017)
Policy support	Bridging the gap on science and policy, e.g. clear policies allowing or restricting reuse programs. Standards and norms and regulations on handling different waste streams, products from valorisation and consumable products made using the waste-based fertilisers/products. Understanding the potential of sustainable procurements though integration of corporate social responsibility into business procurement processes.	Rezaie et al. (2022); Lazurko et al. (2018); Hoff et al. (2018); Grundmann and Maaß (2017); WSP and IWMI (2016); Rizos et al. (2016); Keraita and Drechsel (2015); Saab et al. (2022); Moya et al. (2019a); Lindahl and Dalhammar (2022); Ddiba et al. (2020);

Issue of consideration	Actionable areas	Source
	Economic and financial incentives such as access to loans, viable and acceptable market access, e.g. recognition SMMEs green business models, greening consumer preferences, enhanced market value chains and company cultures.	

2.5 Opportunities and barriers for a circular bioeconomy in South Africa

There are several barriers to the implementation of circular bioeconomy practices in communities. These include knowledge on standards and norms to optimise yields (Simha and Ganesapillai, 2017), minimise environmental pollution (Ogbazghi et al., 2019), protection of workers, their families and consumers from health risks (Keraita and Drechsel, 2015), social perceptions and attitudes (Guo et al., 2021; Moya et al., 2019a; Rosemarin et al., 2020; Simha, P. et al., 2021), institutional, policy and legal issues (Kookana et al., 2020; Moya et al., 2019b), economic viability (Chapeyama et al., 2018; Gougbedji et al., 2021; Medeiros et al., 2021) and market dynamics (Gwara et al., 2023; Mallory et al., 2020; Moya et al., 2019a; Rosemarin et al., 2020).

2.5.1 Technologies to support a circular bioeconomy.

2.5.1.1 Containment technologies

The first consideration in transitioning to a circular bioeconomy is having the appropriate technologies to contain, process and treat the respective waste stream. This section discusses opportunities for establishing a circular economy by exploring available sanitation systems in South Africa, potentially recovered products and how they can be processed in agriculture to establish a circular flow of materials. In this scenario we have the ecosan urine diversion (UD) toilet. Urine diversion toilets were designed with two vaults to separate human excreta into two streams, urine and faecal sludge (Koné et al., 2019). The toilets mimic the human nature of separating excreta into two streams, providing an opportunity to recover urine and faeces/blackwater (Simha and Ganesapillai, 2017). The urine diversion toilet is either found in dry form, e.g. urine diverting dry toilets (UDDTs) or water borne form, e.g. low flush urine diversion toilets (Koné et al., 2019). Ash, wood chips, sawdust or sand can be added in UDDTs to facilitate faster faecal sludge drying and deactivation of pathogens (Taouraout et al., 2018), thus rendering UDDT a pleasant containment technology.

The UDDTs are internationally recommended ecosan toilets, advocated by the ecological sanitation (ecosan) movement as primary sanitation technologies that can be adopted in areas where VIP toilets are difficult to manage (Zurbrügg and Tilley, 2009). These were then introduced to countries such as Morocco (Taouraout et al., 2018), Kenya (Mawioo et al., 2016) and South Africa (Koné et al., 2019). The eThekwini municipality in South Africa then constructed over 75 000 UDDTs by the year 2013 (Udert et al., 2016). Currently only 0.3% of the onsite South African sanitation systems is constituted by urine diversion toilets (StatsSA, 2021) while 7.4% of the households are served by UDDTs (Udert et al., 2016). Meaning that other South African municipalities should learn from eThekwini municipality to facilitate transition to a circular bioeconomy.

Apart from UDDTs, the urine diversion (UD) pour flush toilet is another potential emerging onsite sanitation technology. The UD pour flush toilet has a similar design with the UDDT, the only difference is that it uses about 2 Litres of water for flashing the faecal matter. Since most households aspire to use flush toilets, the pour flush UD toilet is perfect technology for safe and socially acceptable sanitation in off grid areas. The South African research organisations such as the Water Research Commission have been advocating for the deployment of pour flush toilets in rural areas as part of eliminating unsafe sanitation structures (PMG, 2018). This provide an opportunity to link human excreta management with food production in rural areas where wastewater is barely generated.

Safe handling and reuse of human excreta is limited by various human and environmentally health hazardous components (Mallory et al., 2020). Faecal sludge contains more enteric pathogens such as *Ascaris lumbricoides* than urine (Naidoo et al., 2016). This is mainly found in urine in case of cross contamination with faecal matter (Etter et al., 2015). Pharmaceuticals are the major pollutants of concern in urine (Köpping et al., 2020), although their presence have also been reported in faecal sludge (Fijalkowski et al., 2017) and wastewater (Carter et al., 2019). Personal care products have also been detected in wastewater (Kookana et al., 2020). Therefore, human excreta should be treated to reduce pathogen or chemicals of human health concern before agricultural use (WHO, 2006).

2.5.1.2 Treatment of faecal sludge for agricultural use

Co-composting is one of the simple methods for processing faecal sludge into a safe reusable product (Piceno et al., 2017). This has been studied in various countries such as Haiti (Piceno et al., 2017) and China (Cheng et al., 2017) and, currently practised in countries such as Ghana (Nikiema et al., 2014). Co-composting is a method of mixing two different feedstocks, in this case, faecal sludge and other organic materials such as green waste, plant residues or saw dust, followed by conventional composting (Cheng et al., 2017; Cofie et al., 2016; Nikiema et al., 2014). Different feedstocks complement each other as sources of moisture, C or nutrients (Nikiema et al., 2014). During composting aerobic degradation of organic matter increases the concentrations of bioavailable nutrients and at the same time high temperatures (above 55°C) deactivate pathogens (Cofie et al., 2016). When vessel composting is used, high temperatures should be maintained above 55°C for 3 days during the initial thermophilic stage before turning the heap to increase uniformity However, this can be done for 15 day when using windrow composting (Moya et al., 2019b).

Although there are potential benefits of co-compost are reported in Table 2.4, challenges related to its use should be addressed. The rubbish in faecal sludge from most pit latrines needs extra labour for separation. This can be minimised if toilet user education is done to teach people on sustainable solid waste management techniques and refraining from disposing materials in their latrines. The second challenge is malodours, which make handling of faecal sludge unpleasant. Malodours and nuisance are controlled if the faecal sludge is stabilised during pre-treatment.

Table 2.4: Major advantages and possible challenges of co-composting using faecal sludge (Odey et al., 2017).

Advantages of co-composting	Disadvantages of co-composting
▪ Reduces the mass and volumes of feedstock by 50% rendering it compact for transportation. ▪ Aerobic biodegradations increase bioavailable nutrients in compost. ▪ High temperatures achieved during thermophilic stage eliminate pathogens. ▪ High temperatures and release of inhibitory substances reduce weeds viability. ▪ Possible benefits on soil and human health rather than discharging faecal sludge into the environment.	▪ The presence of other foreign objects such as plastics, glass of stones may affect quality. ▪ Lack of adequate knowledge on processes may lead to nuisance and odour generation thereby leading to rejection by communities.

2.5.1.3 Urine treatment

The management of faecal sludge has been discussed in Section 2.5.1.2. This section focuses on valorisation of urine. Urine makes up 1% of total wastewater volume but constitutes to over 80% (N) and 50% (P) (Medeiros et al., 2021), meaning that it is an important source of nutrients, which can be recovered and used in agriculture (Etter et al., 2015). Medeiros et al.

(2021) studied the average nutrient efficiency use values for crops and found out that urine can supply 34% (N), 10% (P) and 4% (K) of total fertiliser required in Brazil. The other advantage is that urine is more sterile and safer to use for agriculture compared to faecal sludge (Taouraout et al., 2018). However, it requires storage for 6 months at 20°C (WHO, 2006) to deactivate pathogens through ammonia volatilisation (Odey et al., 2017). The challenge is that volatilization of ammonia and presence of sulphur generate malodours, and, furthermore, since urine is in liquid form high water content makes its transportation expensive (Udert et al., 2016). Thus, treatment its treatment near generation location is required.

The eThekwini municipality did not have plans to use urine emanating from over 80 000 UDDTs so it was left to drain in soakaways without recovering nutrients (Udert et al., 2016). Therefore, the eThekwini municipality in collaboration with the Swiss Federal Institute of Aquatic Science and Technology (EAWAG) and various scientists explored technologies to valorise urine into safe agricultural products through the Valorisation of Urine Nutrients in Africa (VUNA) project (Etter et al., 2015). The project assessed various technologies that can treat human urine by concentration to make its transportation easier and precipitation to recover some ammonium and phosphorus (Udert et al., 2016).

2.5.1.3.1 Struvite production

One of the technologies assessed is struvite production. Struvite is a solid phosphorus mineral ($MgNH_4PO_4{\cdot}6H_2O$) produced by precipitation of urine at high pH using various Mg source such as MgO, $MgCl_2$ or $MgSO_4$ (Udert et al., 2016). The process was reported to recover almost 95% of phosphates while about 97% of N and other nutrients remain in the solution as struvite effluent after filtration (Etter et al., 2015). To achieve higher pathogen deactivation the struvite can be heated and desiccated (Bischel et al., 2016). Apart from P, struvite production may recover K containing fertilisers if K_2O is used for precipitation (Jagtap and Boyer, 2018). However, studies by Vasiljev et al. (2022) reported that all the nutrients can be recovered from urine following a similar struvite production method by drying at 38°C in alkaline solution (pH >10) of $MgCl_2{\cdot}6H2O\ L^{-1}$ (3.7 g) or $MgSO_4\ L^{-1}$ (2.2 g). The maintenance of pH above 10 prohibits urease catalytic methods and subsequent loss of ammonium thereby recovering all the N from urine and the resulting product contains about 10–11% N, 1–2% P and 2–3% K. The emerging limitation to urine-based technologies is the removal of pharmaceuticals. Some lab scale studies have suggested simple methods such as the use of biochar or granulated carbon to remove pharmaceuticals (Köpping et al., 2020). However, these technologies need community scale co-testing with the farmers to assess scalability.

2.5.1.3.2 Nitrified urine concentrate

A complete nutrient recovery from urine can also be done through two processes that involve nitrification to stabilise the ammonia followed by distillation to concentrate the solution. The process produces a compact liquid fertiliser called nitrified urine concentrate (NUC) which contains all nutrients (Etter et al., 2015). The ammonium stabilisation process makes NUC and odourless and pleasant product. Furthermore, the NUC production process eliminates pharmaceuticals and pathogens, making the fertiliser safe to use (Etter et al., 2015). Currently the NUC product has been endorsed by the Swedish authorities for use even on consumed crops (Vuna, 2022).

2.5.1.4 Wastewater treatment: Decentralised Wastewater Treatment System

The decentralised wastewater treatment system (DEWATS) is a robust onsite technology that can treat wastewaters of various strengths including domestic (greywater, blackwater or brown water) and industrial wastewaters such as textiles and swine wastewater (Gutterer et al., 2009). The DEWATS was tested in various countries including Indonesia, India, China and South Africa (Arumugam et al., 2023; Reynaud and Buckley, 2015; Singh et al., 2019). In South Africa the pilot DEWATS plant was installed by the eThekwini Water and Sanitation (EWS) in an urban residential area (Newlands Mashu) to treat about 35 m^3 day^{-1} of domestic wastewater emanating from nearby 84 households although there are some designed to treat as much as 1 000 m^3 day^{-1} and as low as 1 m^3 day^{-1} (Gutterer et al., 2009). According to Crous et al. (2013) the DEWATS can be connected to Community Ablution Blocks (CABs) in informal settlements or even toilets from schools. Some smaller packages for waste treatment have been reported in Lesotho ate household level (Amoah et al., 2018b).

A schematic diagram describing DEWATS wastewater treatment modules is shown in Figure 2.6. The ABR anaerobically degrade organic compounds from wastewater into inorganic compounds and the resulting effluent is further polished by the Anaerobic Filter (AF), which contains microorganisms to further degrade some remaining compound. The produced AF effluent contains nutrients and pathogens (Reynaud and Buckley, 2015). In hybridised systems, the effluent can be further polished in planted gravel filters (Vertical Flow Constructed Wetlands; VFCW and Horizontal Flow Constructed Wetlands; HFCW). The VFCW aerobically polish effluent while deactivating some pathogens, making the effluent safe for agricultural use due to low COD, BOD and pathogen levels. The occurrence of contaminants of emerging concern (CECs) for example personal care products, pharmaceuticals, microplastics, nano materials, endocrine disruptors and brominated flame retardants (BFR) limits the quality of wastewater for agricultural use (Necibi et al., 2021), and these have been detected in

DEWATS treated domestic wastewater (Abafe et al., 2018). Studies by Mladenov et al. (2021) reported that the DEWATS significantly remove pharmaceuticals and other organic pollutants compared to conventional centralised wastewater treatment plants due to high retention time.

Figure 2.6: An aerial view of the decentralised wastewater treatment system (DEWATS) at Newlands Mashu showing different modules for wastewater treatment. Diagram by William Musazura.

Montwedi et al. (2021) recommended for a systematic shift from high-cost centralised wastewater treatment systems to low cost and sustainable wastewater and resource recovery facilities. From their study they assured that the overall outlook is bright. Which make DEWATS one of the technologies to facilitate a smooth transition to a circular bioeconomy within the South African context.

There are various potential technologies available in South Africa to recover resources (water, nutrients and organic C) for agricultural use. The LaDePa, black soldier fly production, co-composting, urine processing and DEWATS are some of the reviewed mature technologies. However, simple methods such as complete nutrient recovery from urine using wood ash, needs to be assessed at pilot scale in low-income communities.

2.5.2 Best agricultural practices

2.5.2.1 Agronomic practices to maximise crop yields.

Knowledge on best agricultural practices to increase crop yields is important in adoption of circular bioeconomy principles. Studies done under researcher managed conditions show that HEDFs can potentially increase crop yields (Bame et al., 2014; Cifuentes-Torres et al., 2020; Magwaza et al., 2020). The use of treated wastewater in hydroponics and vertical systems is something that has been done using emerging industrial crops such as cannabis (Cifuentes-Torres et al., 2020) and tomato (Magwaza et al., 2020). Sridevi et al. (2016) reported increased maize and French beans yields from the use of urine in combination with farmyard manure, and this was also confirmed by Amoah et al. (2017) using cabbage in Ghana. The same applies to increased cabbage and lettuce yield by faecal sludge + municipal waste co-compost amended soils (Torgbo et al., 2018).

Although HEDFs can increase crop yield, there are also several challenges associated with their agricultural use. Issues such as nutrient imbalances, root zone salinity, leaf scorching, corrosion of irrigation equipment, accumulation of trace elements, soil oxidisable carbon and microbial contamination needs to be well managed when using treated wastewater (du Plessis et al., 2017). Since crops have different nutrient requirements over application of N may cause excessive vegetative growth and delayed flowering (Kookana et al., 2020). Thus, N is a limiting factor used to determine crop nutrient requirements and, in a way, P may be oversupplied (Ogbazghi et al., 2019; Rosemarin et al., 2020; Tesfamariam et al., 2020). Calculating crop N requirements when using treated wastewater such as DEWATS effluent differs from biosolids because the latter is applied once off. However, for wastewater the user may decide if the application should meet crop fertiliser or water requirements. Crop water requirements are not fixed, depend on seasonal variations in climatic conditions, therefore, when full a effluent reuse program is implemented, excessive nutrient loading is expected during dry seasons when irrigation requirements are high (FAO, 2003). Overapplication of nutrients can be prevented by either blending with fresh water, withholding effluent irrigation after meeting crop requirements or even storage for later use (FAO, 2003).

The recommended South African sludge application rate is 10 tons per hectare (Snyman et al., 2006). However this is not the case since N mineralization from biosolids vary across climatic region, soil type and within seasons (Ogbazghi et al., 2016). The South African biosolids N mineralisation is 24% (arid zone), 28% (semi-arid), 29% (sub-humid zone), 37% (humid zone), and 42% in super-humid zone (Ogbazghi et al., 2016; Tesfamariam et al., 2020), meaning that the application of biosolids (e.g. LaDePa pellets and co-compost) should be site specific. This depends on whether the organic fertiliser is used as a soil conditioner or nutrient sources. If the former is true an application of ten tons per hectare is recommended.

Root zone salinity and specific ion toxicity a challenges in use of treated wastewater and urine (Richert et al., 2010). Specific ions such as B, Na^+ and Cl^- can be toxic to sensitive plants if taken up in excessive concentrations (Jaramillo and Restrepo, 2017). Excessive soil Cl^- increases Cd bioavailability and its subsequent uptake by plants to phytotoxic levels (Kookana et al., 2020). Foliage wetting, especially when overhead irrigation is used may lead to scorching of the crop leaves and affect growth. Therefore, surface irrigation systems are encouraged.

2.5.2.2 Managing negative impacts on crop production

The use of treated wastewater has been reported to increase soil salinity especially in arid areas with high temperatures and low rainfall (Hashem and Qi, 2021). High soil Na concentrations may increase exchangeable Na, which decreases soil hydraulic conductivity . However, the action of soil exchangeable sodium may be counteracted by salinity. Hence, sodic soils can be ameliorated with gypsum, which is used as a soil conditioner . Oxidisable carbon loading is one of the issues of concern when Chemical Oxygen Demand (COD) is high. Wastewater with high COD may deplete soil oxygen for microbial activity, thereby impeding nutrient cycling processes (du Plessis et al., 2017). However, studies have reported that the DEWATS treatment processes significantly reduce COD and very low values (68-528 mg L^{-1}) have been reported. The use of DEWATS effluent is less likely to increase soil oxidisable carbon compared to faecal sludge based products, which have a COD range of 3 000-250,000 mg L^{-1} (Odey et al., 2017) while the urine based products range from 250-1 750 mg L^{-1} (Etter et al., 2015), depending on the treatment level. However, there are current guidelines to deal with salinity and excessive nutrient loading. For example, a study by Musazura and Odindo (2021) assessed the suitability of DEWATS effluent for use on different crops in all agroecological regions of South Africa. The authors found out that there are no root zone salinity effects, organic carbon loading, heavy metals loading and effects of wastewater on irrigation equipment. The only issue of concern was the nutrient loading, which the authors suggested that the effluent may be diluted with freshwater.

2.5.2.3 Managing the soil health

The use of HEDFs such as biochar and co-compost increases soil organic C (Moya et al., 2019a) which improve soil physical properties such as cation exchange capacity, aggregate stability, microbial biomass (Nikiema et al., 2014), and moisture retention capacity (Torgbo et al., 2018). However, treated wastewater has high dissolved organic matter (DOM) compared to bio-solids, and this is easily degradable in the soil (Hashem and Qi, 2021). Therefore, long term application of bio-solids increases soil organic carbon compared to the use of treated wastewater. According to studies by Akoto-Danso et al. (2019), application of biochar and irrigation of 13 crops commonly grown in Ghana with treated wastewater increased fertiliser water use efficiency in a Petroplinthic Cambisol soil for over 2 years. This was beneficial to low cation exchange capacity and organic carbon soils making the biochar an important soil conditioner. Increased soil organic carbon due to application of HEDFs stimulate microbial activity, which increase biological degradation of organic compounds from organic fertilisers (mineralisation), leading to increase in soil nutrient bioavailability (Ogbazghi et al., 2016). Mineralisation of organic matter is biological process that is sensitive to edaphic factors such as extreme pH, however, Bame et al. (2014) found that application of ABR effluent increase soil cations, which buffers the soil pH. Meaning that increased soil nutrients and bioavailability due to wastewater irrigation (Hashem and Qi, 2021), application of faecal sludge based HEDFs (Manga et al., 2019) and urine based fertilisers (Alemayehu et al., 2020) can be directly affected by nutrient composition of the HEDF or indirectly by their effects on the soil ecology.

It has previously been discussed that HEDFs increase soil nutrients, whereby some drawbacks are related to direct impacts on crops. In addition, there are other environmental challenges likely to be encountered. Nitrogen and phosphorus are two major nutrients of environmental concern (Sharpley, 2016). The soil N is mostly lost to the groundwater as nitrates due to its solubility and the process is faster in well drained coarse textured soils compared to clay soil types (Ogbazghi et al., 2019), while P is mainly lost through soil erosion and surface runoff (Sharpley, 2016). Management practices such as application of nutrients in excess of those required by crops (Ogbazghi et al., 2019) and poor irrigation management practices (Musazura et al., 2019a, b) may lead to environmental pollution. Ogbazghi et al. (2016) suggested that the sludge should be applied to meet the crop N requirements taking into consideration the mineralization rate, which is affected by soil type and climatic condition in various agroecological regions. Therefore, any biosolid based HEDF such as co-compost or black soldier fly residue should be site specific. Musazura et al. (2019b) reported that irrigating banana to field capacity with DEWATS effluent increased soil N and P content in high clay soil (Sepane soil; Aquic Haplustalf) but the nitrate leaching was high in acidic soil with more organic matter soil (Inanda soil; Rhodic Hapludox) and P leaching was high in sandy soil (Cartref; Typic Haplaquept). This means that high clay soils have low hydraulic conductivity to retain more nutrients in the root zone where they are less likely to be leached but remaining as potential pollutants if lost to the surface water resources via surface runoff, depending on slope, irrigation management, tillage practices and rainfall. The loss of nutrients in sandy soil is via passive drainage and the nitrate leaching is a major concern in acidic soils.

2.5.2.4 Trace elements pollution and bioavailability

Accumulation of trace elements in the soils is caused by anthropogenic activities such as application of biosolids in agricultural fields and accidental discharge of industrial wastewater into the environment (Olowoyo and Mugivhisa, 2019). High concentrations of trace elements in the soil can be phytotoxic and dangerous to the food chain. A review by Olowoyo and Mugivhisa (2019) showed that the bioavailability of trace elements depends on soil organic matter, soil pH, redox potential of the soil and type of crop grown. Trace elements have been reported in wastewater contaminated with industrial wastewater, e.g. textiles (Fijalkowski et al., 2017) and various faecal sludge-based products such as the ash fraction of biochar (Krueger et al., 2020) than those found in urine (Etter et al., 2015; Richert et al., 2010). Trace elements are found in sludge than wastewater because they are adsorbed by organic matter from faecal sludge. However, studies have confirmed absence of trace elements in domestic DEWATS effluent, making it safe to use. A review by Semiyaga et al. (2015) reported that naturally faecal sludge do not contain any trace elements unless contaminated. Therefore, presence of trace elements in faecal sludge from onsite sanitation systems is related to user behaviour, such as disposing old batteries and even hair saloon wastewater into pit latrines. Special attention should be directed to the concentrations of trace elements in sludge-based products such as co-compost, biochar, BSFL and its residues than in DEWATS effluent and urine-based products.

2.5.2.5 Emerging pollutants

Contaminants of emerging concern (CECs) are chemicals that are currently not included in the waste management programs and have potential environmental and human health problems (Mladenov et al., 2021; Necibi et al., 2021). These are problematic in low-income countries where they are extensively used (Kookana et al., 2020) and advanced wastewater treatment is expensive and not prioritised (Necibi et al., 2021). Therefore, they should be given special attention (Singh, 2021). Evidence shows CECs can be found in wastewater (Abafe et al., 2018; Necibi et al., 2021), urine and faecal sludge (Fijalkowski et al., 2017; Olowoyo and Mugivhisa, 2019) and the environment; surface water, ground water and soils (Kookana et al., 2020). However, mechanism on their persistence in the soils, uptake by plants and subsequent transfer into the environment is not well understood as reported in many studies (Necibi et al., 2021; Olowoyo and Mugivhisa, 2019; Singh, 2021). In addition, the CECs include pharmaceuticals which may increase antibiotic resistance of pathogenic and non-pathogenic bacteria (USEPA, 2012). This also further raise a question about how the pharmaceuticals affect soil health with focus on microbial communities, abundance and activity in relation to nutrient recycling. However, the major challenge is that these studies have been done under scientific conceptual thinking which differ from context specific expectations, making the transition process difficult. The farmers need to understand several issues such as application rates, soil testing and recommended management practices to prevent some issues such as nuisance, pollution and crop contamination. Thus, adequate training and guidance is needed capacitate local farmers with ability to apply best agricultural practices that will attain higher or maintain existing yields in their farms.

2.5.3 Human health and safety

One of the key barriers to the use of HEDFs in agriculture are the perceived health risks. Several papers have reported on the potential impacts of pathogens in HEDFs (Amoah et al., 2018c; Bischel et al., 2016; WHO, 2006). Pathogens of concern include viruses (e.g. rotavirus and bacteriophages), bacteria (e.g. *Enterococcus*, *Escherichia coli* and *Salmonella*) and parasites such as helminths ova (e.g. *Ascaris*) (WHO, 2006). Helminths eggs are the most problematic because of their persistence in harsh environments including soils and are considered as the most important benchmark to assess potential health risks from a certain HEDF (Keraita et al., 2014; Naidoo et al., 2016; WHO, 2006). A review by Guo et al. (2021) showed that SARS-CoV-2 is one of the emerging pathogens detected in human excreta that should be given attention.

Different pathogen exposure risks for various actors across the food and sanitation value chains have been reported in the literature. Sanitation workers and farmers working with human excreta are exposed during collection, handling and transportation (Cheng et al., 2017; WHO, 2006, 2016). One of the exposure pathways include unhygienic practices by sanitation workers and farmers who may expose themselves and their families to pathogens after work (Richert et al., 2010). Koné et al. (2019) found parasitic helminths from examined face masks of manual pit emptiers. A study by Cofie et al. (2007) showed that farmers from Tamale, Kumasi and Bolgatanga (Ghana) and Mali were applying untreated faecal sludge in their fields, and found to exhibit some foot rot and itching symptoms. The authors recommended adequate education for proper handling and hygiene practices when working with faecal sludge.

In cognisance to perceived health risks when using HEDFs, the World Health Organisation (WHO) established guidelines for safe excreta use in agriculture. Previous WHO guidelines (1978 and 1985) focused on human excreta treatment, which was a challenge in most low income countries which barely met total pathogen elimination from excreta due to technological and financial constraints (WHO, 2006). Integrated approaches such as the WHO multi-barrier concept were developed to minimise health risks across the entire sanitation value chain (Moya et al., 2019b; Richert et al., 2010; WHO, 2006). Several scientific developments have been done on various approaches to minimise exposure of workers, farmers, families and consumers to enteric pathogens. The WHO, in consultation with a panel of scientific experts and various stakeholders, developed a systematic approach called the Quantitative Microbial Risk Assessment (QMRA) tool to assesses the exposure risks through various pathways (WHO, 2006). The QMRA has four components: (i) hazard identification, (ii) exposure assessment, (iii) dose-response assessment, and (iv) risk characterization. A review by Jaramillo and Restrepo (2017) showed that microbial laboratory tests and epidemiological studies can be used in parallel with QMRA but, depending on the local context, this might be expensive and impractical. Meaning that this can be challenging in developing countries such as South Africa.

A multi barrier approach explained in Figure 2.7 is one of the methods advocated by the WHO to minimise microbial risk across the sanitation value chain. Technologies to contain and pre-pre-treat human excreta were discussed in Section 2.5.1. According to the WHO (2006) excreta treatment should target at least <1000 cfu/100 mL (wastewater) or <1000 cfu/g (solid HEDF) of faecal coliforms and <1 viable helminths egg/L (wastewater) or <1 helminths ova/4 g (solid HEDF) to minimise pathogen transmission risks when applied to food crops. Cossio et al. (2021) from Bolivia reported that the use of treated wastewater minimises microbial transmission risks than raw sewage and this was confirmed by Amoah et al. (2018b) using DEWATS effluent in Lesotho. However, Torgbo et al. (2018) reported contrasting results that sometimes faecal sludge based co-compost might be less riskier to use compared to conventional fertiliser due to presence of trace elements, which according to them, can deactivate pathogens in the soil. Meaning that sometimes transmission of pathogens might not be solely related to the HEDF applied and this agrees with du Plessis et al. (2017) and Fuhrimann et al. (2016), who reported that sometimes excess amounts of faecal pathogens, exceeding <1000 cfu/100 mL have also been reported in surface water and stormwater.

There are various field management practices to minimise contamination of food products from HEDFs and protecting the consumers and farmers from exposure to pathogens. One of the application techniques which prevent direct contact with edible part is the use of surface irrigation instead of overhead irrigation on crops that are eaten raw, e.g. lettuce. Therefore, surface irrigation methods are recommended because they protect the farmers from dermal contamination, the public from drifting effluent and the consumers from ingestion risks (WHO, 2006). Crop restrictions such as production of crops that can either be cooked or processed is one of the mitigation strategies. Workers and farmers are at risk from eye, dermal and accidental ingestion of contaminated HEDFs hence strict occupational health protocols such as vaccinations and the use of Personal Protective Equipment (PPE) should be enforced and adhered to (WHO, 2006). Unhygienic practices during post-harvest handling provides another pathway for product contamination. Integrated practices such as withholding HEDF application over a period before harvesting, avoidance of picking up produce that have fallen to the ground, washing and treatment with a disinfectant, and even processing can help eliminate pathogens and minimise risks to consumers (WHO, 2006). However, food safety is not only limited to pathogens, even CECs and trace elements can be harmful. It is, therefore, vital to ensure that their concentrations are within the acceptable limits. A scoping review with metanalysis done by Adegoke et al. (2018) showed that occurrence of antibiotic residues and resistance genes have been found in crops irrigated with wastewater. The authors further emphasised that the risk quotient for their bioaccumulation in aquatic organisms is remarkably high. However, these needs to be monitored in crop tissues.

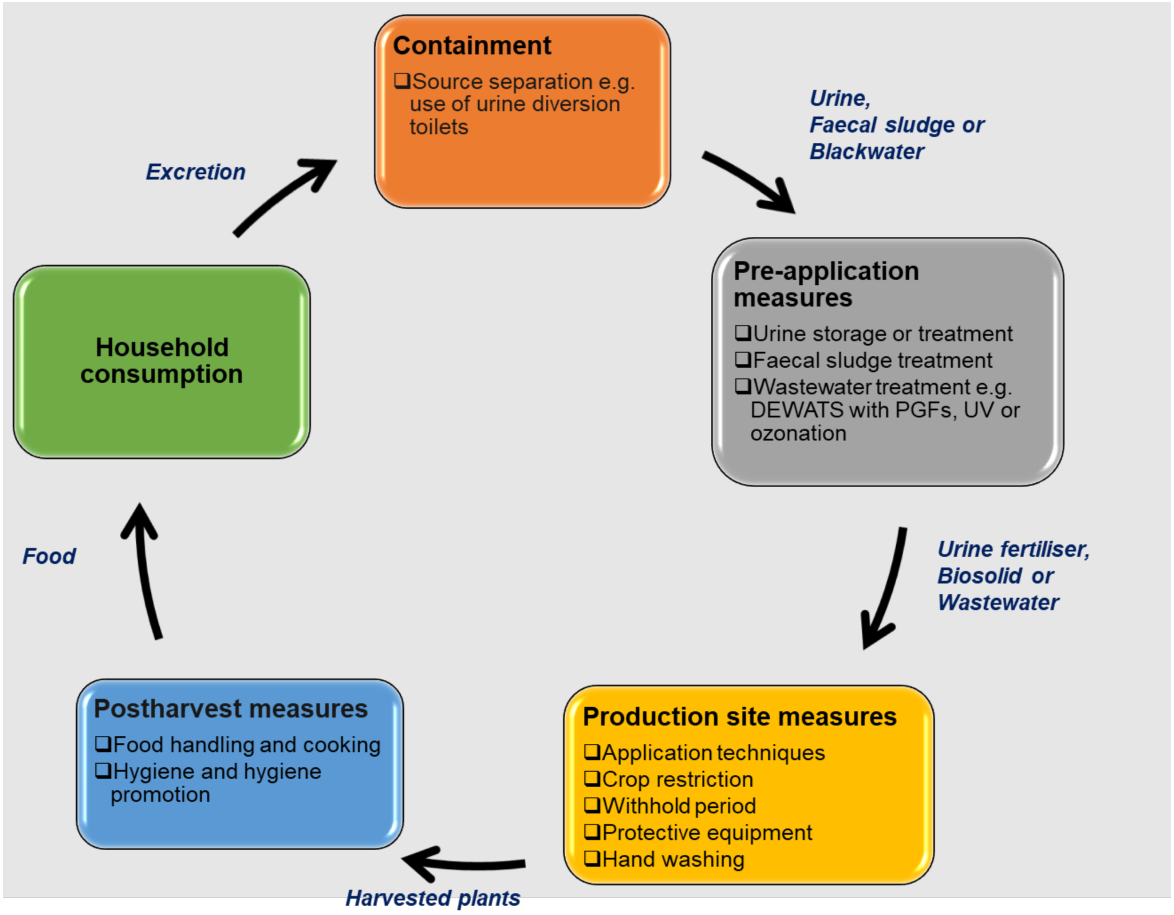

Figure 2.7: A schematic diagram on several steps in a multi barrier approach to minimise health risks associated with the use of HEDFs at various stages of the sanitation and food value chain. Diagram adopted from Richert et al. (2010) and modified by William Musazura.

The implementation of a multi barrier health risk assessment in HEDFs use programs can be done in accordance with the recently established WHO risk-based management tool called the sanitation safety plan (SSP). The SSP apply WHO (2006) guidelines principles to promote safe agricultural use of human excreta. The tool can be used by various actors along the sanitation value chain, and these include local authorities, entrepreneurs and farmers. The tool was tested with the National authorities in Hanoi, Vietnam; Manila, Philippines; Benavente, Portugal; Karnataka, India; Lima, Peru and Kampala, Uganda under the guidance of a panel of experts (WHO, 2016). Several authors recommended it as an instrumental tool to minimise health risks in excreta reuse programs (Adegoke et al., 2018; Amoah et al., 2018a;

Fuhrimann et al., 2016). The SSP is a stepwise approach that comprises of various modules described in Figure 2.8.

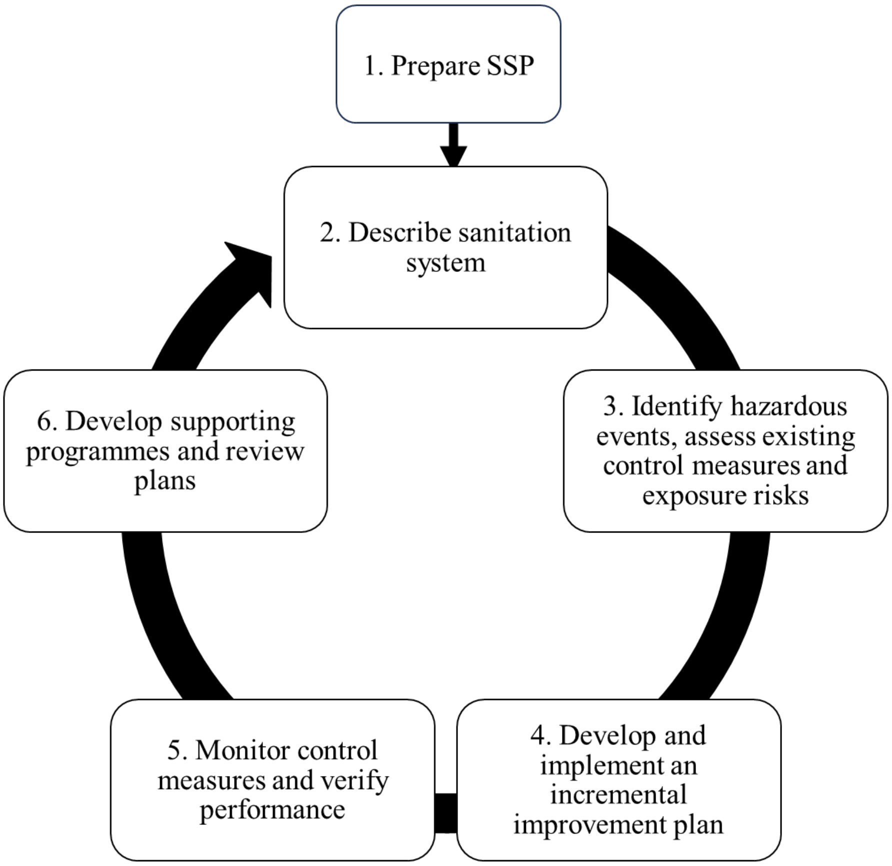

Figure 2.8: Various modules of the stepwise Sanitation Safety Planning (SSP) approach. Adapted and modified from WHO (2016).

As a move to transition to a circular economy, South Africa may make use of the SSP as recommended by Odindo et al. (2022a). However, current evidence shows that about 7 out of 44 wastewater treatment plants in Ghana are operating below minimum standards and over 11 500 ha of land is informally irrigated with wastewater (Khalid et al., 2018; WWAP, 2017). The farmers are even irrigating over 15 kinds of vegetables (WWAP, 2017). There are reports that although farmers are provided with risk management strategies they are not complying (Keraita et al., 2014). A survey done in Almeria, Spain by López-Serrano et al. (2022) showed that farmers referred to lack of compliance by the irrigation community as a challenge in spite of established strict regulations, in which the interviewees, believe the public administration should ensure that wastewater is treated to meet standards. Therefore, interventions such as educating people across the value chain, penalising non-compliant entrepreneurs and using participatory methods to co-design safe treatment systems were suggested (Keraita et al., 2014). A scoping review and metanalyses done by Musazura and Odindo (2022) showed that the domestic DEWATS effluent after HFCW treatment does not meet WHO standards for unrestricted agricultural use. However, empirical findings by Saab et al. (2022) showed that the use of treated wastewater with <2Logs of *E. coli* does not significantly contaminate vegetables that can even be eaten raw. Advanced and standard wastewater treatment methods were also suggested by Kesari et al. (2021). Studies by Russo et al. (2019) integrated UV technology and constructed wetlands to treat domestic wastewater and it met strict Italian and European union standards for unrestricted agricultural use in terms of pathogen loads (<1 log). Hence, sustainable post treatment technologies to improve irrigation water quality are needed as South Africa transition towards the circular economy. This help deal with challenges such as educating people about good hygienic practices, which they are likely no to follow.

2.5.4 Social perceptions

Social dynamics play a role in a circular bioeconomy transitioning process. Several reviewed studies have highlighted myriad social barriers to successful transition towards a circular bio economy (Etter et al., 2015; Okem and Odindo, 2020; Simha et al., 2020). These barriers are likely to be encountered across the sanitation value chain from containment technologies, collection, transportation, treatment technologies, use in agriculture and consumption of the end products (Okem and Odindo, 2020; Simha et al., 2018). Several barriers in question include perceived health risks (Keraita and Drechsel, 2015; Mallory et al., 2020; Moya et al., 2019a), lack of knowledge on potential benefits and willingness to adopt new technologies (Guo et al., 2021), cultural beliefs (Massoud et al., 2018; Taouraout et al., 2018), the yuck factor (Ricart and Rico, 2019) and lack of information on viable business models in reuse programs (Mallory et al., 2020).

Positive attitudes and perceptions towards the agricultural use of HEDFs have been confirmed in South Africa and beyond (Amoah et al., 2017; López-Serrano et al., 2022; Mamera et al., 2020). One of the identified reasons behind social acceptability is understanding the circular bioeconomy as a mitigation strategy for environmental pollution and public health risks. According to Amoah et al. (2017) educating people about the use of urine as a fertiliser may change their perceptions as a “resource” not “waste”. Okem and Odindo (2020) interviewed people from five rural and two urban areas of South Africa and confirmed their willingness to use treated wastewater for agriculture. The authors suggested that such technologies may be integrated with existing indigenous norms related to recycling and reuse and this was confirmed by Wells et al. (2016) in USA. A study done in India where 1 252 consumers were interviewed, 68% of them reported to understand the need to reuse the human excreta in agriculture and 55% of them understood HEDFs as valuable fertilisers (Simha et al., 2018). Mamera et al. (2020) conducted a study in Monontsha Village of Free state South Africa, where 17% of the interviewed people abandon toilets when they are full. About 69% of the respondents suffered from diarrhoeal diseases due to poor sanitation and hygiene. As a result of that 60% of the respondents were willing to use human excreta for agriculture. Thus, education on the importance of excreta recycling should be incorporated during community engagement process. Empirical evidence provided on key attributes driving willingness to pay for the fertiliser products (Gwara et al., 2023; Simha, P. et al., 2021). These attributes include certification by relevant trusted authorities, labelling to increase attractiveness and value addition of the products, for example fortification of the compost (Otoo et al., 2018).

Rezaie et al. (2022) suggested that the transition should have a component of “just transition”. Meaning that it should tackle issues such as gender roles, youth and women empowerment. South Africa is a country battling high unemployment and poverty driven unrests amongst the youths and female headed households (Chakona and Shackleton, 2019; StatsSA, 2021). However, a study done by Wilde et al. (2019) to assess the willingness of farmers to use HEDF in Msunduzi, South Africa showed that young individuals were more willing to use nitrified urine for agriculture. In addition to that women are the major actors in agriculture from production to marketing and likely to encounter some cultural issues such as male dominance (Taron et al., 2021). These gender issues need to be addressed and well understood for a successful transition in a social inclusive way.

The previous paradigm was centred towards flush and forget when it comes to water borne sanitation. The same applies to onsite sanitation, for example, the 1994 South African White Paper on Water and Sanitation focused on household sanitation without a resource recovery component encompassing safe collection, transportation treatment and end use. However, the current paradigm have a component of safe recovery and reuse (DWS, 2016). This entails consideration of faecal sludge containment technologies such as ecosan toilets (e.g. UDDTs). Despite UDDTs being ecological sanitation toilets, they once faced resistance by eThekwini local communities (Etter et al., 2015) as was the case in China (Guo et al., 2021). This was because users did not know potential benefits such as resources recovery. However, Salisbury et al. (2018) proved that the acceptance rate of such technologies is high when people are provided with proper education.

User aspiration should be taken into consideration during the planning process. For example, it is apparent that majority aspire to use flush than dry toilets as evidenced in South Africa (StatsSA, 2021). According to Simha, P. et al. (2021) wastewater treatment plants (WWTP) are trusted as best solutions to treat human excreta for agricultural use. However, high establishment and maintenance costs of WWTPs make them impractical for future sanitation especially in developing countries battling with intense urbanisation. However, off-grid sanitation systems remain the best options to be considered in the future. Therefore, this is the time to rethink on selecting appropriate containment technologies, understand user preferences and integrate with resource recovery. For example, integrating low flush urine diversion toilets with emerging water borne sanitation systems such as the Decentralised Wastewater Treatment System (DEWATS) (Arumugam et al., 2023). This hastens uptake of some resource recovery technologies such as UD toilets by majority of poorly served communities in an equitable manner.

Although farmers are willing to use HEDFs in their fields, people may be hesitant to consume the produced crops due to perceived health risks (Keraita and Drechsel, 2015; Mallory et al., 2020; Simha, P. et al., 2021). This is because people do not have adequate knowledge on treatment procedures to eliminate pathogens despite the availability of scientifically proven technologies and protocols to minimise health risks (Simha, P. et al., 2021). Further strengthening the need for transformative approaches to transition from existing food systems to circular sanitation bioeconomy. Simha, P. et al. (2021) interviewed 3 763 people from twenty universities in sixteen countries and concluded that 59% of respondents were willing to consume food produced using HEDFs. However, the authors reported that the willingness ranged from 14% (in Jordan) to 80% (in China). Results could be attributed to the target group of formally educated people from universities but the enormous range in willingness to consume could be show some differences in cultural beliefs. Meaning that people will consume food produced using HEDFs if they are assured that it is safe to do so through certification by relevant authorities (Grundmann and Maaß, 2017). However, product certification and labelling should consult relevant authorities and social groups such as traditional leaderships, religions and consumer council, to strike a balance between marketing and consumer protection. For example, the use of labels does not go against certain religious practices rather than labelling as “faecal sludge product.”

Although Ignacio *et al.* (2018) found out that <25% of sampled farmers in Philippines were not willing to use human excreta for food production, despite >50% of the sampled farmers knowing their importance as potential fertilisers, substantial evidence shows that the willingness to consume resulting food products is not a barrier. In fact, it depends on how the case has been presented to target groups. According to Adapa et al. (2016) 7Ps (product, price, place, promotion, people, process and physical evidence) approaches in marketing are crucial in influencing consumer satisfaction. Apart from willingness to consume food from urine fertilised crops, a review by Simha, P. et al. (2021) further showed a wide variation in the willingness to pay for the premium price amongst respondents from various countries. Interviews and focus group discussions done by Frijns et al. (2016) in various European wastewater reuse schemes showed consumers perceive food produced using treated wastewater as high quality compared from conventional practices. This presents an opportunity to explore several market niches; with adequate market research farmers or retailers selling food products made using HEDFs can be able to understand best quality and value addition options to maximise profits.

2.5.5 Economic and financial viability

According to Lindahl and Dalhammar (2022) the circular bioeconomy is not only about saving natural resources but should also focus on improving livelihoods. Rezaie et al. (2022) suggested that circular supply chains and business models should be understood regarding how local businesses connect with global or even regional value chains, exploring opportunities for marginalised groups and economies of scale in circular economy. Meaning that circular economy principles should be integrated with current business paradigms across the value chains. This can be influencing existing markets to accommodate new circular economy products and establish a financially sustainable system.

There are several studies that have probed into economic and financial viability of running sanitation linked resource recovery and reuse (RRR) business models (Amoah et al., 2017; Mallory et al., 2020; Otoo et al., 2016; Tesfamariam et al., 2020). The economic and financial viabilities are two contrasting aspects (Table 2.5). Financial viability focuses solely on cashflows part of it while economic viability takes a broad spectrum of sustainability indicators, ranging from environmental, social as well the financial gains themselves. For example, Grundmann and Maaß (2017) reported that agricultural use of wastewater and sludge as the final step of the wastewater treatment value chain reduces the disposal costs. Therefore, the focus will be given on economic viability. Otoo et al. (2016) provided a guideline on a methodological framework for the feasibility assessment of circular economy business models in developing countries. Such business models are pertinent in guiding investors willing to participate in circular economy business. For example a study done on over 41 countries around the world showed that some developed countries such as Singapore and Australia have made progress in safe agricultural use of wastewater due to extensive collaborations, with the former country being strong in advanced reuse technologies while the latter providing expertise in stakeholder engagement (Lautze et al., 2014). Currently, South Africa does not have established wastewater irrigation business models and case studies, therefore, there is need for strong collaborations in establishing and co-testing wastewater reuse business models through international and local collaborations.

Table 2.5: The comparison of financial and economic viability in RRR business models. Adapted from Otoo *et al.* (2016).

Financial analysis		**Economic analysis**	
Costs	*Revenue*	*Cost*	*Benefits*
▪ Marketing and distribution of resources ▪ Storage costs ▪ Retrofitting ▪ Treatment	▪ Sales or revenue from resources recovered	▪ Costs for no action ▪ Marketing and distribution of resources ▪ Storage costs ▪ Retrofitting ▪ Treatment	▪ Benefit of increased prosperity and resilient communities ▪ Benefits of protected public health and ecosystems ▪ Benefits of improving waste management ▪ Benefits of cost savings though new resource supply and sales revenue ▪ Benefit of cost savings reduced disposal

Barriers to economic viability of circular economy models include technological costs (Rezaie et al., 2022), operational costs (Tesfamariam et al., 2020) and returns from sales (Moya et al., 2019a). According to Semiyaga et al. (2015) technologies should be affordable, made from locally available materials which are easy to maintain at household and community level, have commercial applications and able to occupy existing space even in informal settlements. Technologies such as DEWATS and co-composting fit to this criterion. However, the challenge arises with production of scale to meet financial profitability. This issue has been raised in several literature (Cofie et al., 2016; DFFE, 2020a; Otoo et al., 2018). There are approaches to estimate economic viability of certain circular bioeconomy interventions. For example, approaches to calculate the substitutive savings of using the respective fertiliser based on several parameters. For example, Tesfamariam et al. (2020) took an agronomic perspective to assess economic viability of organic fertilisers. They calculated minimum economically viable transportation distance for a municipal sludge containing N (3%), P (2%) and K (3%) as 20 km (arid zone) and 75 km (super humid zone). Meaning that it is more profitable to produce and transport co-compost in super humid areas if you are the producer and end user.

Lack of incentives to support circular economy initiatives is another barrier especially to emerging small scale entrepreneurs. Melati et al. (2021) highlighted that sometimes products from a linear economy models might be lower costing, giving them a competitive advantage. Small-scale compost production is not viable. However, large scale compost production by small scale enterprises might be limited by high establishment costs to purchase machinery (Lazurko et al., 2018). Increased production at scale has multiplier socio-economic benefits such as employment creation, indirect local economic development and significant impact on minimising waste generated into the environment as well as interfering with economic activities such as tourism. Institutional intervention like governmental subsidies on operational costs may help businesses to sustain themselves if operating at scale (Melati et al., 2021). Otoo et al. (2016) called for a change in thinking from public sector driven sanitation management based on “treat and dispose” to private sector driven practice such as “waste to wealth” approaches in RRR. The same model has been tried in China, whereby, according to Cheng et al. (2017) a municipality contracted a private company to produce non-commercial compost for their landscaping. In Kenya, Sanergy (Pvt Ltd) is shifting from being solely a waste management entity into a large scale commercial enterprise looking forward to variate production of profitable human excreta based products such as BSFL, hydrothermal carbonisation and pyrolysis, and anaerobic digestion of faecal sludge (Moya et al., 2019b). The Sanergy product diversification strategy ensures higher returns on sales and this was also supported by Lazurko et al. (2018).

One other barrier that can be taken into the lens is marketing. Markets for the circular economy products, e.g. co-compost are available as reported from a case studies conducted in Kenya and Haiti (Moya et al., 2019b). Several studies showed that certification of circular economy products may increase demand for the products (Gwara et al., 2023; Keraita and Drechsel, 2015; Otoo et al., 2018; Simha, P. et al., 2021). Even value addition for example increasing the nutrient value for co-compost through fortification, is one of the ways to enhance market demand for the resulting product (Gwara et al., 2023; Otoo et al., 2018). This idea should not only be based on input supply side but can be applied on the post-harvest handling of crops produced using circular economy fertiliser. Rizos et al. (2016) studied circular economy business models barriers and enablers for SMMEs within the European context. The authors recommended that European and national policies should focus more on changing consumer preferences, market value chains and company practices, and spearhead the support of SMMEs’ green business models. They recommended, for example, creation of resolute marketplaces and communities of practice.

Several options can be taken into considerations to increase revenues in circular bioeconomy models; these can be value addition through small scale processing, choosing high value crops that fetch high sales returns for example flowers, seedlings and even producing black soldier fly and its products. Small scale processing to add value minimise potential food losses across the value chain and in a way save production energy costs lost as food waste. However, the global GAP (good agricultural practices) which is the commonly used standards for certification of agricultural products (e.g. horticultural crops) do not allow the use of sewage sludge in certified farms (Moya et al., 2019a). In this case substantial global and local market research to leverage niches in which the circular economy intervention/business can operate profitably and legally is needed.

2.5.6 Institutional, policy and legal issues

Despite having established technologies, in both mature and immature stages; to contain, collect, process and recover resources from human excreta, available knowledge on the impacts of using HEDFs and respective mitigation strategies, the implementation of circular bioeconomy is still lacking in low-income communities. Barriers can be broadly categorised into enabling policy environment, financial, infrastructural and technical capacity, business support services and markets (Kesari et al., 2021; Otoo et al., 2016). For example, unclear policies at global and local level (Hoff et al., 2018), poor institutional support due to poor policy coherence across governmental organs (Moya et al., 2019b), access to financial support (Lazurko et al., 2018) and regulations to support international trade of HEDFs to competitive markets (Hoff et al., 2018; Moya et al., 2019a; Rezaie et al., 2022).

On international scale, Europe is taking a progressive approach in reviewing their circular economy policies to accommodate its interaction with the world. Hoff et al. (2018) stated that the European Union bioeconomy strategy can take three approaches which are "*in Europe*", "*by Europe*" and "*with Europe*". The "*in Europe*" entails that sustainable consumption of goods and services by integrating supply and demand side measures, thus, promoting local bioeconomy. When it comes to "*by Europe*" the focus will be on a role played by the EU in zooming the global lens of the circular economy while "*with Europe*" the focus will be on creating global North and South partnerships to nurture technology and innovation sharing, trade commons and skills combination in circular bioeconomy transition. This provides an opportunity for African countries to adjust their policies with the emerging European markets. This is possible, for example, in South Africa if governmental departments such as Department of Trade and Industry and Competition (DTIC) to play a role in establishing policies to boost competitive advantages for SMMEs to penetrate the international market.

One of the major barriers to circular bioeconomy transition is institutional interests. Internationally reviewed governmental policies from myriad countries explicitly focus on waste streams other than human excreta (Steinfatt, 2020). Even the South African research institutes and municipalities are mainly concerned with municipal solid waste while biogenic waste attention is only given to food waste (DFFE, 2020a; DFFE and DSI, 2020; Godfrey and Oelofse, 2017; Pretorius et al., 2023). The eThekwini municipality is one of the few municipalities that have been playing a pivotal role in supporting science and innovation towards sanitation linked bioeconomy (Harrison and Wilson, 2012; Salisbury et al., 2018; Udert et al., 2016). Lack of institutional interests pose challenges such as bias towards waste specific waste stream management, lack of technical and infrastructural investments to support reuse and financial allocation towards sanitation waste. The South African Municipal Systems Act 2000 (Act No. 32 of 2000) give municipalities legal obligation to implement their specific waste management strategies, flexible for them to even practice “treat and dispose” rather than “treat and reuse” as per their waste operating licence according to the National Environmental Management (NEMA) Act, 1998 (Act No. 107 of 1998) (DFFE, 2020a) and the National Water Act (NWA) No. 36 of 1998 (DWS, 2022). The same corroborates findings by Ddiba et al. (2020) who reported disconnection between public awareness for circular economies and the need for urgency by public sector, disconnection between the postulated practices than activities on the ground and the minimal involvement of public sector in organic waste management compared to private sector.

Bossle et al. (2016) identified law enforcement as the major driver towards adoption and implementation of eco innovations. State of Green (2021) emphasised the need for the public sector participation in areas such as public procurement to stimulate demand for circular bioeconomy products though right framework conditions and financial incentives. Thus, a change in thinking is needed for South African institutions to consider an obligatory component of a circular bioeconomy while the laws and policies should be adjusted to enforce the practices as mandatory to a certain extent. Furthermore, policy change should be done in alignment with international interests in platforms such as African Circular Economy Alliance and the European First Circular Economy Action Plan.

Going deeper into the South Africa context. There are governmental organs with policies centred towards supporting the transitioning to a circular bioeconomy. For example, the South African national sanitation strategy (DWS, 2016). The South African waste management strategy considers interdepartmental coordination to support innovations and private partnerships in waste valorisation (DFFE, 2020a). Furthermore, the South African government has an agenda to eliminate hunger and improve livelihoods in communities through just transition targeting women and unemployed youths. Thus, the South African DWYPD (2020), though not directly linked to circular bioeconomy, it has policies that can be adopted. The DWYPD supports economic transformation, entrepreneurship and job creation for youths and women. The South African Bureau of Standards (SABS) and the Consumer Goods Council of South Africa may play a pivotal role in standardising human excreta reuse programs as is being done in Lebanon (Saab et al., 2022). A coherent policy on waste recycling linking governmental organs across the waste and food value is needed. This will foster several functions of a circular bioeconomy, e.g. financial, technical, legal, business, compliance, and market access across the food value chain. The Enhance Project (2021) in Europe has been advocating for policy change to support competitiveness of circular bioeconomy models by supporting eco management and audit schemes (EMAS). Meaning strong involvement of civil society in support of green business models is necessary in South Africa.

Institutional support regarding financial support is another barrier. Enterprises such as co-composting have high establishment costs as well high liquidity risk due to longer returns on investments (Lazurko et al., 2018). This is hard for small entrepreneurs to access loans, meaning that the transition process is deviating from the just transition consideration. Although private sector investment to nurture partnerships with small enterprises might be an option, it is still not clear on how to establish sustainable mutual interaction for "win-win" on both ends. According to Lazurko et al. (2018) the public sector can only be attracted if there is proven demand and profitability. Thus, more demonstrations and piloting of scalable circular bioeconomy technology is a solution.

Working in silos is the major barrier. Transition to a circular economy is a complex process which take several factors such as enabling environment with regards to policy coherence, enhancing food value chains and financially, technically and institutional capacitation. This needs a transformative approach at local level to establish a bottom up approach in a social inclusive manner, involvement of policy makers, financial institution, private and public sector, regulatory boards and academia (DFFE, 2020a; Khalid et al., 2018; Lazurko et al., 2018; Steinfatt, 2020). Which, according to Ddiba et al. (2020), cross sectoral collaborations can be spearheaded by the public sector in their capacity as local, regional or national authorities.

2.5.7 Summary and conclusions

The summary and conclusions emanating from the study are shown in Table 2.6.

Table 2.6. Conclusions and recommendations in respect to the research questions.

Research question	Conclusions	Recommendation
To what extent are the South African technological advancements, policy and legal frameworks supportive of human excreta recycling initiatives?	South African legal framework supports the use of HEDFs. The major challenge is that these policies are implemented in silos, leading to lack of policy coherence across all governmental organs. The same applies to institutional interests, most local municipalities and research institutions are centred around municipal solid waste with little or no attention given towards human excreta.	Policy renewals from the municipal level to regulators to shift current waste management paradigms from linear approach to obligatory circular bioeconomy are needed. For example, enforcing an obligatory target level for sustainable human excreta management, and a strict monitoring and reporting system.
What are the technical, social dynamics, human health, environmental and economic barriers prohibiting the transitioning to a circular sanitation bioeconomy linking sanitation to food systems in South African communities?	Social perceptions and attitudes are not barriers if the end users. Assurance that the circular bioeconomy fertilisers are safe to use as well as the consumption of crops especially when certified by regulatory boards. Some people can adopt the circular bioeconomy principles if given adequate education. Farmers need assurance on agricultural performance of circular bioeconomy fertilisers in comparison to their conventional practices	Farmer engagement should consider indigenous practices and norms as well as involvement of beneficiaries in each stage of the transition process. Technical capacity building on best practices for human excreta use by target groups can be administered through trainings and progress monitoring of circular bioeconomy interventions are needed to ensure compliance.

Research question	Conclusions	Recommendation
	and potential market niches for resulting products. . Apart from substantial technological advancement, South Africa has put in place adequate best practices and guidelines for agricultural use of human excreta derived fertilisers. The use of human excreta derived fertilisers is not limited to human health risks. This is due to established best practices such as the implementation of a sanitation safety planning.	More studies are needed on integrating advanced treatment technologies as obligatory components of the Sanitation Safety Plans to treat wastewater to pathogen levels that allow WHO unrestricted agricultural use. Economic feasibility of incorporating advanced treatment technologies in different components should also be assessed.
	Economic viability of circular bioeconomy interventions is one of the barriers. Most interventions such as co-composting needs to be done at scale to be profitable which is not possible for small scale entrepreneurs. Small scale entrepreneurs do not have access to microfinances so they cannot invest in state of art technologies. In this case there are potential indirect economic gains such as improved resource efficiency, cleaner environment and	The farmers should be educated about maximising profits from such interventions through diversification of activities at the farm level, e.g. value addition and production of high value crops. Therefore, business models are important to assess economic viability, and provide evidence-based information for private sector investors to engage in profitable circular bioeconomy activities. Private

Research question	Conclusions	Recommendation
	reduction in public health hazards. There are protocols to manage health risks, and these include the multi-barrier approach risk assessment and implementation of the World Health Organisation Sanitation Safety Plans (SSP). However, the SSP principles are rarely implemented by users, posing health risks across the food value chain.	investors are crucial actors in technological investments through public-private partnerships.
What are the strategies to facilitate transformative approaches in successful implementation of circular bioeconomy models linking sanitation with food systems in South African communities?	The competition for linear economy products is higher than circular bioeconomy interventions. The future on access to international markets such as the European union is promising, with such countries considering circular bioeconomy policies to include their trade partners.	The government may intervene by providing subsidies to minimise industrial competition with linear economy products. The South African government may capitalise on this opportunity by connecting with the international platform through partnerships in eco-innovation research and development, policy change and enhancing food systems to allow large scale and small-scale investors access lucrative international markets. A multilateral approach inclusive of different

Research question	Conclusions	Recommendation
		stakeholders, academia, consumers, policy makers, local communities and traditional leadership, and regulatory boards to be brought on board in support of establishing a circular bioeconomy is the solution.

3 SOCIAL CONTEXT STUDIES: STAKEHOLDER MAPPING, CHARACTERISATION AND ENGAGEMENT

3.1 Introduction

The recovery of water and nutrients from human excreta and organic waste and agricultural use is a sustainable way of minimising pollutants entering the environment and over extraction of natural resources. Transitioning from conventional linear materials flow food systems to closed loop is a complex process. Key thematic areas of consideration for circular bioeconomy transition process are best agricultural practices to maximise crop productivity while minimising risk associated therewith (Andersson, 2015; FAO, 2003; Richert et al., 2010), social perceptions and acceptance of products and interventions (Gwara et al., 2023; Kookana et al., 2020; Wilde et al., 2019), clear regulatory frameworks and policies for compliance (Lindahl and Dalhammar, 2022; Moya et al., 2019b; Rezaie et al., 2022), availability and accessibility of local and international markets (Otoo et al., 2018), availability of economically viable business models (Lindahl and Dalhammar, 2022; Otoo et al., 2018; Rezaie et al., 2022), social inclusion, e.g. vulnerable groups such as women, youths and previously disadvantaged (Khalid et al., 2018; Taron et al., 2021) and appropriate technologies for safe treatment according to regulatory limits (Nansubuga et al., 2016; Odey et al., 2017; Ricart and Rico, 2019; Russo et al., 2019). Such transitioning dimensions needs an integrated approach (Table 2.6).

Transitioning to a CBE needs a paradigm shift from "silo" way of practicing and thinking to transdisciplinary and collaborations in innovation platforms. Several studies support the need for transformative approaches involving extensive transdisciplinary interactions across value chains as the best approach to speed up the bioeconomy transition process (DFFE, 2020a; Khalid et al., 2018; Lazurko et al., 2018; Steinfatt, 2020). These actors, e.g. academic specialists, communities members and champions, policy makers, public and private institutions across both the food and sanitation value chains, can participate in co-identification of context specific challenges, co-create best approaches to deal with the problem, co-test and co-validate proposed intervention to aid transfer, adoption, acceptance and up scaling of resilient or sustainable innovations in CBE (Ddiba et al., 2020; Schut et al., 2019). Currently the RUNRES project has established these multistakeholder innovation platforms in four countries including South Africa (RUNRES, 2023; Sekabira et al., 2022; Sekabira et al., 2023).

Building from previous work (WRC K5/2777), which generated a practical guideline for agricultural use of huma excreta, the current study seeks to transition from academic research to community-based action study through "living labs". Hossain et al. (2019) defined a living lab as a place where societal challenges are solved by bringing together stakeholders for collaboration and co-production of knowledge. They further characterised it as landscapes, methods, real life environments where different stakeholders apply several business models and approaches to resolve societal issues. Issues such as temporality, governance, user recruitment, scalability, unpredictability, and sustainability are major challenges faced in such systems.

This section reports on project triggering process by engaging with the RUNRES innovation platform for research synergies and collaborations. The engagement was done with the communal farmers, women and youth owned cooperatives for co-identification challenges they are facing in agricultural production systems. The study proposed, co-identified and characterised relevant food and waste value chain stakeholders to address such challenges, and co-developed a sound participatory research roadmap to co-test the practical applicability of using HEDFs in agriculture. The studies were guided by the South African context guideline that emanated from the previous project (Odindo et al., 2022b). The section discussed and outlined lessons learnt during the identification and engagement of stakeholders and their active participation.

3.2 Methodology

All the materials and methods were developed and used to apply for ethical clearance. The researchers applied for the Human Social Sciences Research Ethics Committee (HSSREC) ethical clearance since the study involved interactions with the community.

3.2.1 Study site mapping

The project worked synergistically with the RUNRES platform and the local municipalities (eThekwini metropolitan and uMsunduzi local municipalities). According to Leventon et al. (2016) the stakeholder identification and engagement process for transdisciplinary studies is a rigorous and iterative process which should be done in accordance with the project expected outcomes. The project engaged with the RUNRES which had previously established a well-functioning transdisciplinary innovation platform (Sekabira et al., 2023) and participated as an academic research stakeholder. In addition to that the project previously had working relationships with the eThekwini municipality which provided an agricultural testing site at Newlands Mashu. The final research locations identified were within the uMgungundlovu district (uMshwati, uMsunduzi and uMgeni) and eThekwini metropolitan municipality. Each innovation was mapped in accordance with project activities across the sanitation and food value chain.

3.2.2 Target community groups identification and engagement

The study area boundary and target population were clearly defined. The target group within communities were small scale farmers from rural and peri/urban areas. Groups of famers operating with the study area were identified from the RUNRES transdisciplinary innovation platform during various workshops conducted. The first agricultural production systems mapping workshop was done at Madlala community hall in Vulindlela. The activity led to identification of women cooperatives aspiring to do poultry and crop production for processing. The cooperatives included RUSUS, Isihlakoti, KwaQanda and Sobantu.

The KwaZulu-Natal Christian Council (KZNCC) was identified during further engagement within the RUNRES platform. The KZNCC is a Non-Governmental Christian Organisation based in KwaZulu-Natal. The organisation has a memorandum of understanding with the National Christian Economic Development Agency (NCEDA). The KZNCC own different church farms around the province including the 7ha of land at Bishopstowe in Pietermaritzburg. The NCEDA played a role in introducing the project members to some co-operatives they were working within in Sobantu. Some cooperatives from the KZNCC network were identified in Howick and Appelsbosch after further engagements and consultations. The farm manager from Appelsbosch was identified and selected as a key informant. Key informant interviews were done to introduce the project and discuss potential research collaborations. Discussions to understand their existing practices, challenges faced and available mitigation strategies if available were done after a meeting with farmers.

3.2.3 Community engagement

Participatory Rural Appraisals (PRA) were done to co-identify existing challenges in farmers agrosystems, co-identify research questions and co-develop road map for sustainable agriculture research and community demonstration plots (Figure 3.1).

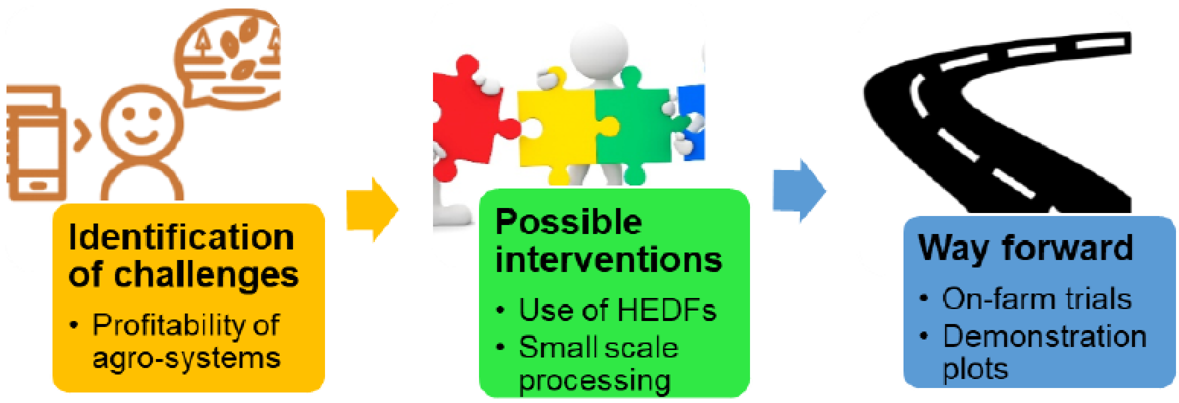

Figure 3.1 Roadmap to community-based research with identified cooperatives.

3.2.3.1 Engagement with Vulindlela farmers

The Participatory Action Research (PAR) was done in Vulindlela with women cooperatives from KwaQanda and Isihlakoti. The workshop was conducted at Vukuzakhe Community Hall, KwaZinqamu, Vulindlela, Msunduzi where four women attended. The others that could not attend conveyed their apologies.

The circular bioeconomy concept linking sanitation with food systems was introduced. Innovative technologies to valorise human excreta, good agricultural practices and standards and norms for safe reuse, and the importance of agro-processing was explained in local language.

The participants were divided into various groups, provided with markers and whiteboard papers to list challenges they are facing across the food value chain from input supply, farming, transportation and marketing. The participants discussed respective solutions to the challenges they have identified. Each group presented their findings, which were collated together. The participants broke down into their respective groups to discuss potential small scale processing opportunities. A give and take matrix exercise was used to identify potential areas of collaborations and knowledge sharing as a roadmap to implementation was clarified. However, feedback and the farmer engagement process with all members including those that could not make it was continued over the WhatsApp group, which was created as a permanent communication platform during the project. This provided an opportunity to utilize emerging technologies for better communication amongst small scale farmers.

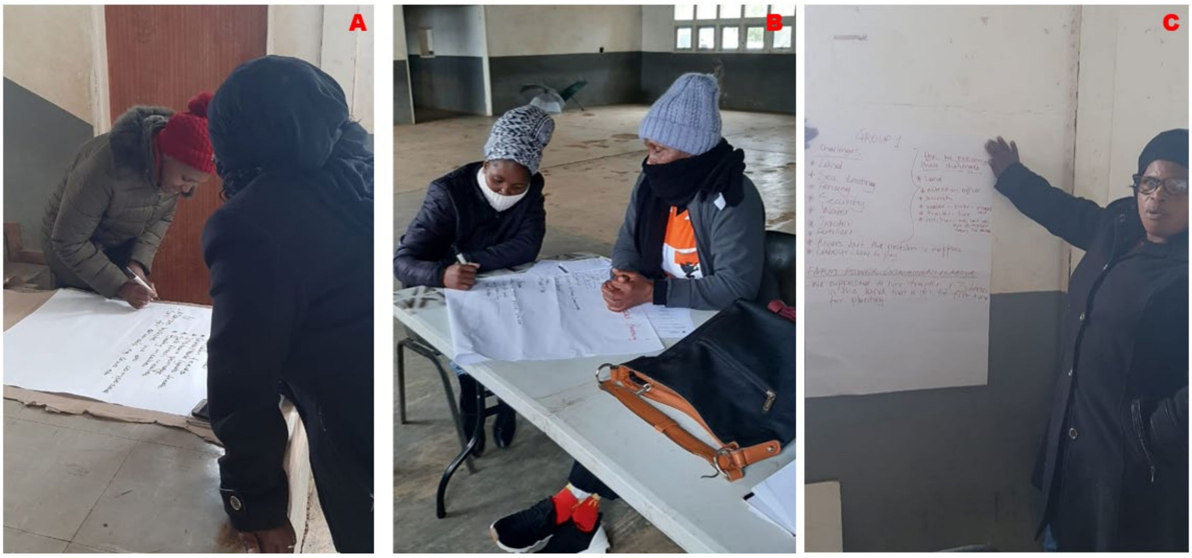

Figure 3.2. Women owned cooperatives discussing challenges and opportunities for small scale processing in their agricultural systems (A and B) and presenting to the whole PRA group (C).

3.2.3.2 Engagements with NCEDA and KZNCC

The initial meeting between the UKZN, NCEDA and KZNCC was done on 4 May 2022 at KZNCC office in Pietermaritzburg. The main agenda was to trigger a working relationship between the UKZN and NCEDA by identifying common grounds for knowledge exchange and collaborations. Further engagement with NCEDA continued and the organisation introduced other four cooperatives (Sakhubuntu, Mfenendala, Sobantu and Tholulwazi) working conjointly within the KZNCC network. A kick-off workshop was then organised and conducted to trigger a working relationship (Figure 3.3). Proceedings included introduction of the project to the members, discussing existing agrosystems and food value chains of interest from each cooperative and potential agro-processing options.

Figure 3.3. The University of KwaZulu-Natal students, KZNCC leadership and cooperatives (A) and the leader of youth owned NCEDA cooperative presenting their intended agricultural activities at a meeting held at Bishopstowe farm hall (B).

3.2.3.3 Engagements with Sobantu cooperative

The PAR was done following methods recommended by Nyumba et al. (2018). The research questions were drafted in consultation with the team members. The PAR participants were selected from the local farmers identified within the RUNRES transdisciplinary innovation platform. The research team members from the University of KwaZulu-Natal were catalysts to ensure smooth proceedings. One of the female students with strong background of the native language was selected as the PAR assistant and master of ceremony.

The program started with introductions and consent statement was conveyed to the participants. They were informed that their participation was voluntary and free to withdraw any time. The participants were requested to fill in the attendance register should they consent to participate.

The PAR leader provided a brief background of the project from its activities under researcher managed controlled conditions and transition to research for community development using the transformative approach in living lab. The community participants were broken down into various working groups according to age, gender and expertise based on information provided during introductions. All the proceedings followed a detailed program outline and guiding protocols.

Figure 3.4. Brainstorming sessions for women's group (A) and males' group (C) followed by their presentation of findings (B and D).

A session was done to assess the perceptions and expectations from CBE interventions. Each group conducted a rich picture session to describe and discuss challenges they are facing in their food systems across the whole value chain from input supply, crop production, post-harvest handling and marketing. A second rich picture session was done to identify an envisioned system after the introduction of proposed CBE interventions. Participants proposed small scale processing value chains using different coloured cards for each category, crop type, processing options and products, and market opportunities. The capacity of the target group to spearhead proposed value chains in accordance with the explained circular economy principles was assessed using a SWOT analysis. The participants were ungrouped and arranged randomly, everyone proposed different stakeholder/institution or company that can (i) play a role in facilitating the functionality of the identified value chains; input supply, production, processing and marketing/retailing and (ii) address identified challenges per each value chain.

3.2.3.4 Stakeholder identification and characterization

The stakeholders were selected for their relevance across the food and waste value chains based on information emanating from the PAR. The identified stakeholders were aligned with potential contribution to solving challenges identified during the PRA exercise. The stakeholders were contacted for interviews but in case for those that were not contactable, their potential contributions were assessed based on the public available information on their websites and institutional publications.

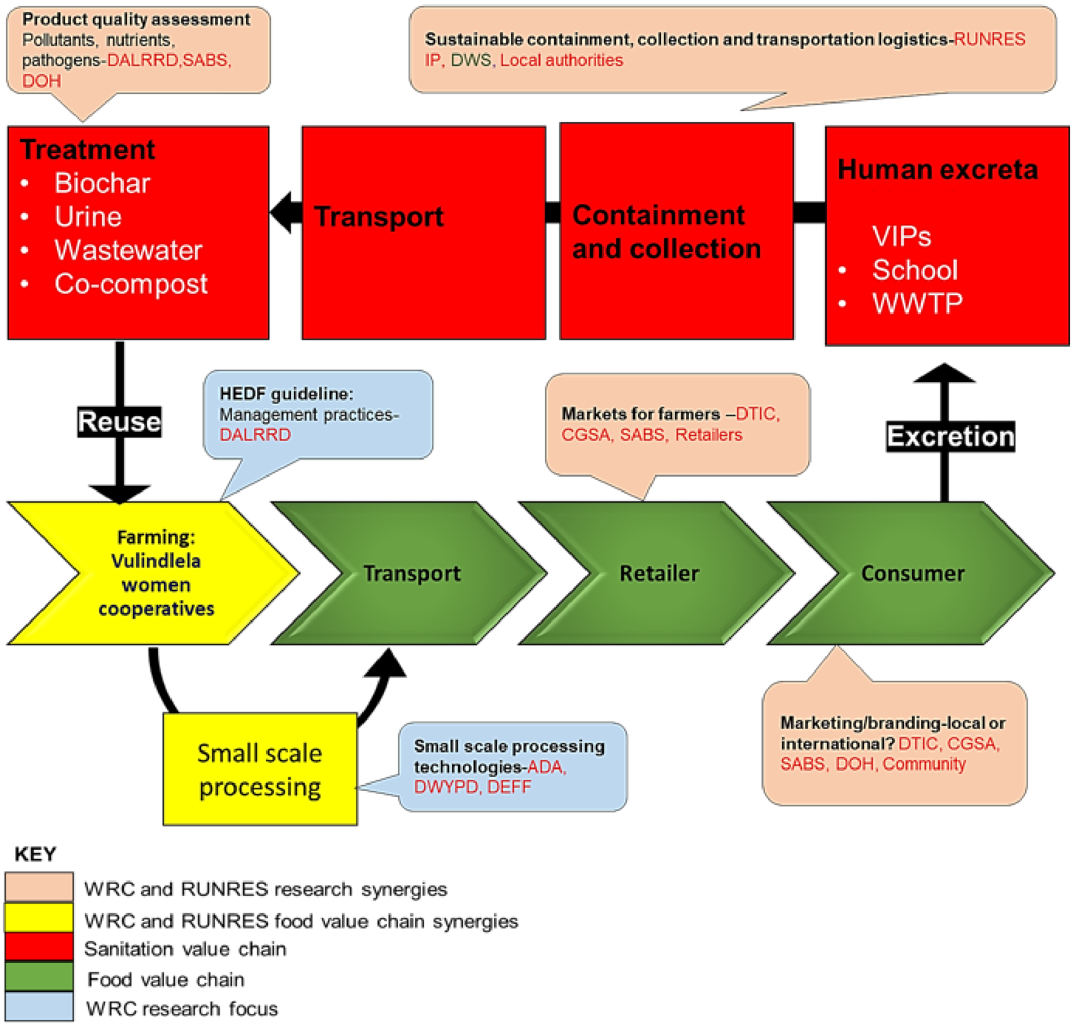

Figure 3.5. Identified synergies between the WRC project and RUNRES across the food and waste value chains (Diagram adopted from the RUNRES model and modified to suit the research context).

3.3 Results and discussion

3.3.1 Study sites mapping

3.3.1.1 Vulindlela

Vulindlela is the largest rural community of uMsunduzi local municipality where socio-economic challenges such as poor faecal sludge management, food security and high poverty levels are predominant. In cognizance of poor fecal sludge management from predominant pit latrines in the area, waste valorisation innovations that have potential to solve existing challenges while improving livelihoods as well as public health were considered. The RUNRES wanted to establish a biochar production innovation.

Biochar is a hygienic and stable carbon product made from pyrolysis of organic matter. These organic matter include fecal sludge, saw dust, garden waste, food waste and even agricultural residues (Khan et al., 2021). Biochar is a multipurpose product that can be used for agriculture as soil conditioner, industrial ingredient for cosmetics and even in wastewater treatment. Depending on pyrolysis conditions and feedstock type, large quantities of ash may be yielded in comparison to the biochar. The ash is a potential feedstock to produce stabilized alkalized urine fertiliser (Vasiljev et al., 2022).

During the engagements with the community, a potential biochar and agriculture site was identified near Serfontein prison (29°44'00.8"S 30°08'45.6"E) see Figure 3.6. The area had approximately 6ha of land which and was secured by the farmers. About 2ha was allocated for both the co-composting, biochar production and crop trials during the pilot period (<5 years). Several activities were undertaken including site surveying. However, actual activities could not materialize due to gatekeeper’s interests which forced the project team to exit the study site.

Figure 3.6. Site visit to assess the biochar and co-composting facility and an aerial view of the facility in proximity to the agricultural trials field.

3.3.1.2 Julukandoda

The Julukandoda primary school is in KwaDulela, uMgeni local municipality under the uMgungundlovu district municipality, KwaZulu-Natal (29°35'49.3"S 30°11'43.2"E). The school was identified and engaged by the RUNRES. The urine diversion low flush toilets connected to DEWATS innovation is being constructed there (currently near completion at the time of writing). The innovation is expected to provide treated wastewater and urine for tree seedlings production. The extra urine generated from the site will be processed into safe and sterile fertilisers for agricultural use. The DEWATS does eliminate pathogens for unrestricted agricultural use (Amoah et al., 2018b; Musazura and Odindo, 2022) and pharmaceuticals (Mladenov et al., 2022) so studies on the advanced wastewater treatment technologies were planned to be done there. Due to delays which were outside the project timeframes the wastewater treatment studies were then done at the UKZN using treated effluent from the DEWATS in Newlands Mashu.

The project made breakthrough by meeting up with a private company that designed an ozonation machines for wastewater treatment. Watermed (PTY) Ltd is a Durban based private company offering water treatment technologies. The organisation designed and patented a portable steriliser using ozone gas in a portable container. The organisation seeks to treat wastewater for aquaculture and hydroponics, which aligns with the project idea of integrating such technologies to polish DEWATS effluent for unrestricted agricultural use. The double benefits of such technologies are efficient ozonation to degrade organic compounds while removing pathogens. The agricultural use of wastewater is a common practice in countries such as Ghana, where raw sewage is used to irrigate crops such as lettuce. Despite having sanitation safety guidelines and farmer trainings to promote safe agricultural use of wastewater, farmers do not practice multi barrier approaches to minimise pathogen risks (Drechsel et al., 2014). The project was supposed to collaborate with Watermed and include such technologies in producing high value crops using DEWATS effluent. Intensive crop production using hydroponics allows all year production in areas where land is limited. The production of high value crops brings high returns per unit area and time. Thus contributing to establishment of economically viable intervention that motivate farmers (Frijns et al., 2016).

3.3.1.3 Newlands Mashu

Research and innovation are important aspects in CBE transitioning process through learning and evaluation of existing and emerging technologies, optimizing processes and fitting technologies into context specific scenarios (Rezaie et al., 2022). The Newlands Mashu research facility located in Durban North (29°46'24.8"S 30°58'27.2"E) owned by the eThekwini metropolitan municipality is a research center where learning and evaluation of DEWATS innovation was done in alignment with identified communities' context while waiting for the community plant to be constructed.

The facility consists of a 35 m^3 capacity DEWATS plant to treat household wastewater generated from 84 households. The DEWATS was designed by the Bremen Overseas Research and Development Association (BORDA) and commissioned by the eThekwini Water and Sanitation department. The technology consists of the settler, anaerobic baffled reactor (ABR), anaerobic filter (AF), planted gravel filters (horizontal flow constructed wetlands; HFCW and vertical flow constructed wetlands; VFCW). The facility has a greenhouse and a field (1 500 m^2) reserved for agricultural trials.

Due to the presence of an established DEWATS the site was chosen for experiments on agricultural use of treated wastewater through food crops seedling production, ornamental plants, and high value vegetable crops. The site provided testing platform for co-compost and urine derived products. The established and reliable DEWATS system allowed inclusion of advanced and other innovative wastewater treatment technologies to meet quality for unrestricted agricultural use. The treated wastewater was used to produce high value profitable crops.

The proposed collaboration with Watermed could not take off as proposed and planned. There was a site break-in which delayed the whole process as the private company had to rethink about security investment. Theft is a serious issue when it comes to installing innovative technologies in communities. This is not new but common in South African communities. A study done in four South African cities by Roberts and Shackleton (2018) found out that the occurrence of community gardens is spatially and temporarily dynamic. Theft of infrastructure has been identified as one of the reasons for the disappearance of community gardens and called for context specific interventions with this regard.

3.3.1.4 Bishopstowe Agricultural Living Laboratory

The KZNCC owns 7ha agricultural farm located in Bishopstowe, uMshwati local municipality under uMgungundlovu district municipality (29°35'10.5"S 30°28'46.7"E). The farm is currently used for on farm trials, demonstration plots, production of crops and a hub for small scale agro-processing of crops produced using human excreta-based materials. The proposed activities on the site were seedling production using co-compost. Different human excreta treatment activities to be done included urine stabilisation using ash from the pyrolysis residues, urine storage, struvite production, co-composting of pit latrine faecal sludge and farm residues. With interaction between different stakeholders the site was designed by the RUNRES as a living lab where different stakeholders (research institutions, cooperatives, NGOs and communities) conduct research, demonstrate and learn agroecology. The project role was to drive agricultural trials, demonstration plots and support agro-processing research.

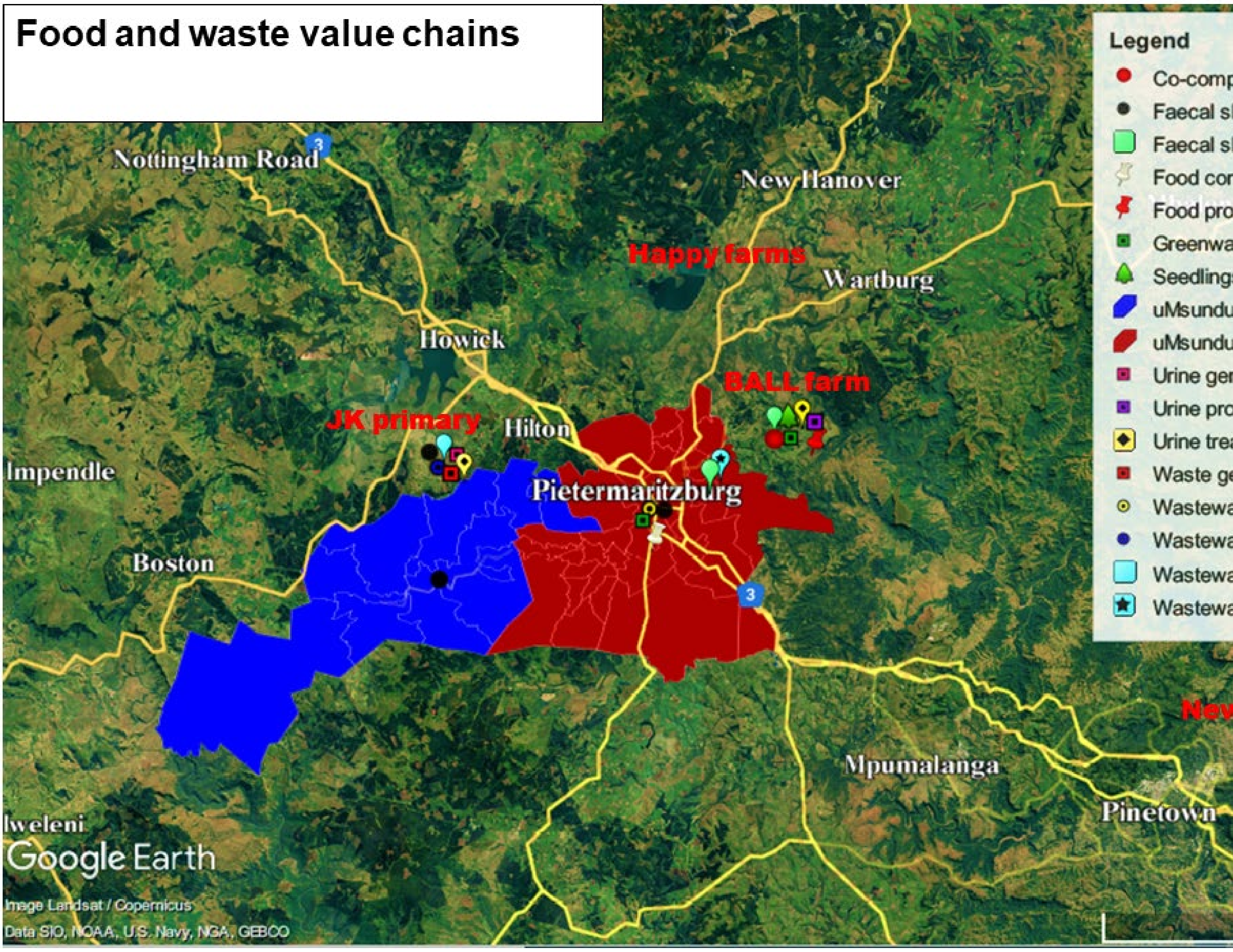

Figure 3.7. The identification of study sites for linking innovative sanitation technologies and agricultural use. JK refers to Julukandoda Primary School.

3.3.2 Community engagement

3.3.2.1 Vulindlela case study

The challenges and solutions identified and discussed by the two women cooperative groups from their agricultural production systems are shown in Figure 3.8. This section discusses opinions by small scale farmers from Vulindlela.

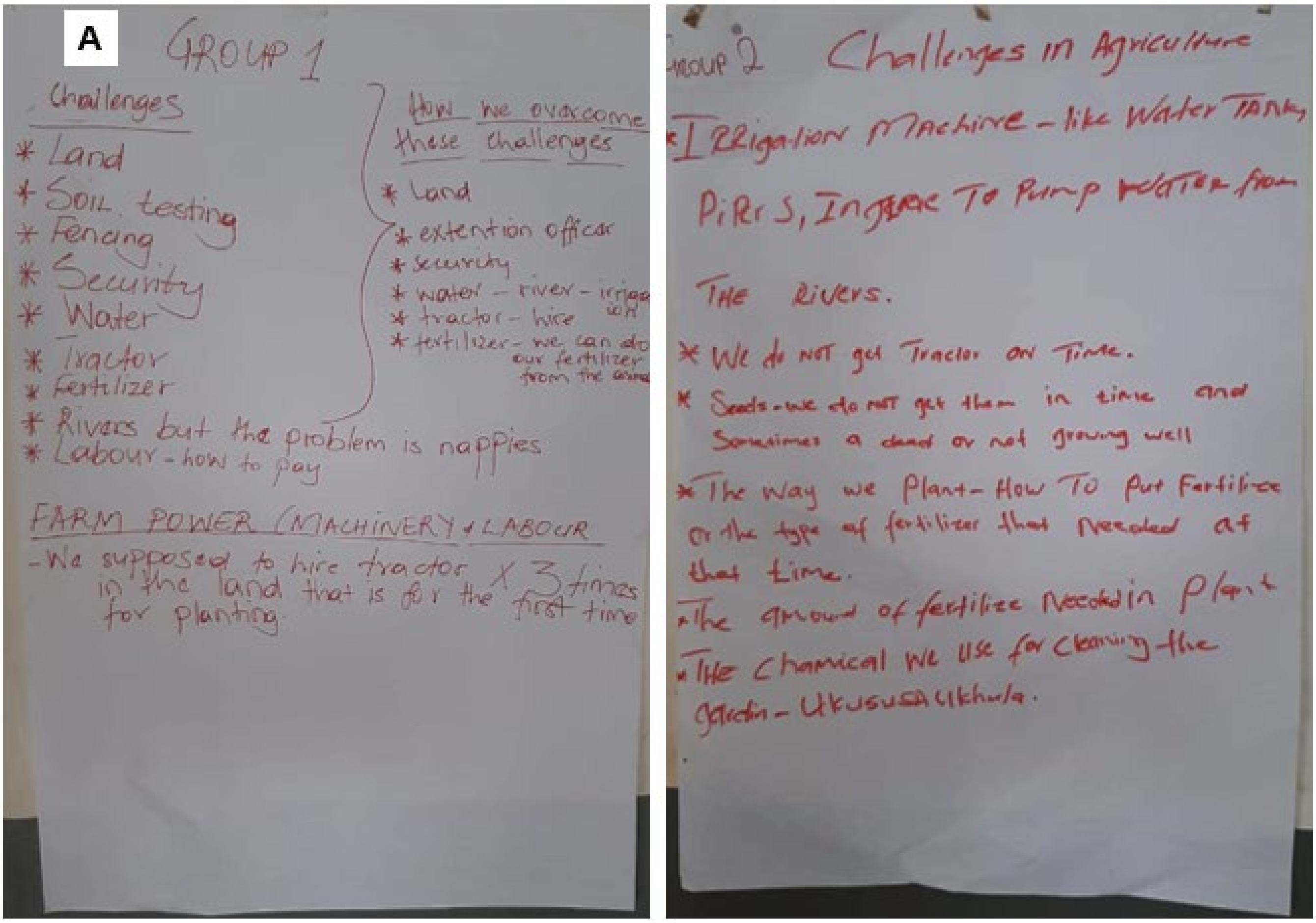

Figure 3.8. Challenges and solution to existing agricultural systems of the target farmers

The identified challenges and solutions discussed are summarised in

Table 3.1. These were mostly land tenure, soil testing, water quality and quantity, crop protection, labour availability and market access.

Table 3.1. Summarised agricultural production challenges encountered by the two cooperatives and potential solutions identified during the PAR.

Challenge	Solution
Land tenure	Negotiation with traditional leadership.
Soil analysis	Consultation with DALRRD extension on available support to small scale farmers.
Theft	Investigating several security measures.
Water quality and availability	Selecting a site close to a river. Ensure that the water quality is assessed.
Financial stability	Hire tractors from private operators -self independence on equipment hire, equipment purchasing

Fertilizer costs and application methods	Alternative fertiliser sources such as animal manure. Farmer training from UKZN scientists.
Labour cost	Group operations
Seed viability	Purchasing seed from reliable sources. Self-propagation of planting materials.
Weeding operations	Farmer training from UKZN scientists.
Valid markets	Contract farming

The first challenge was land tenure. Farmers who rent privately owned land do not have security to invest in immovable properties. Most participants lived in rural areas where the agricultural land is owned by the traditional leaders. The land can be obtained on a long-term basis through the permission to occupy (PTO) provided you have a plan to use it productively. One of the participants was interested in poultry farming for eggs but could not do that because they lacked proper infrastructure. Efforts to outsource funding where fruitless because of missing documents which is the title deeds to provide evidence of land ownership. Since the South African rural land is mostly owned by traditional authorities, occupants do not have title deeds for the full control of land (Williams-Wynn, 2021). That problem cannot be addressed if the traditional leaderships and relevant governmental authorities engage each other. This is the responsibility of the DALRRD (DALRRD, 2022a).

The cooperatives are financially constrained to operate agribusiness economies of scale. As a result they are not able to pay for labour, purchase equipment, conduct soil analyses and crop protection practices such as weed, pests and diseases control. They cannot afford to purchase their own machinery such as tractors and irrigation equipment. They rely on government support for operations such as ploughing and disking which according to them the service is sometimes unreliable. One of the participants highlighted that they sometimes receive a tractor for land preparation when the planting season has gone. This affects their planting calendar.

Soil fertility is a challenge considering that the small-scale farmers don’t afford chemical fertilisers and they have limited capacity to test soil nutrients. One of the participants mentioned that they are not able to test for soil for fertility prior to planting because they don’t have the technical and financial capacity. As a result they either over or underapply fertilisers unsustainably in their agricultural field. This is crucial in the bioeconomy transition process, for example knowledge on best agricultural practices centred around nutrient management in the use of HEDFs minimise environmental pollution.

Adequate training and technical support on general agricultural management practices such as soil fertility management, crop protection, preharvest and postharvest handling and other agribusiness management skills such as writing business proposals is required. Training packages may be provided by the academic institution to capacitate them with agribusiness management skills, which will benefit them even after the completion of the pilot phase. According to Bizikova et al. (2020) training farmers is vital to enhance their understanding of sustainable agricultural practices. This allows them to adopt them in their conventional practices.

Theft has been factored out as one of the challenges faced by farmers. This seems to be a general problem in many South Africa communities, even a study by Roberts and Shackleton (2018) reported that 36% of the respondents interviewed in Eastern cape household gardens suffered from theft and equipment damage in their agricultural field. Theft of agricultural produce may not directly contribute to losses but may affect the farmer planning. For example the farmer may harvest unripe produce in fear of theft (Denning et al., 2009). The authors attributed this to socio-economic issues such as food insecurities and absence of incentives to buffer the poor communities. However, during the PRA, cooperatives suggested that fencing may solve this problem but this is a complex issue that needs an integrated approach involving intensive community engagement to create a sense of ownership on respective green technologies. Roberts and Shackleton (2018) preferred to having no fencing as a better positive solution. During a research by Etter et al. (2015) one of their community experience in relation to theft was that labelling urine collection containers with the term “urine” deterred people from stealing. In this regard, labelling the fields with “faecal sludge manure used for crop production” written in local language may alleviate this. Education and strong community involvement by educating communities on the consequences of theft may help. Depending on scale of production, employing local people as workers in the agricultural fields may create a sense of protecting income sources. Most importantly investing in a security guard may be a good option as well as an employment creation strategy. This aligns with the ideology by Roberts and Shackleton (2018) who felt that community gardens should be areas for development and poverty alleviation in rural areas.

The availability of reliable water supply is one of the identified problems. According to the farmers, they could not have agricultural fields close to a river. The issue of water-energy-food nexus comes into lens. The DALRRD may play a pivotal role in drilling solar powered boreholes in strategic locations around farming areas. This address intertwining water crisis faced by communities using renewable energy in energy insecurity areas of South Africa. The same practice is also being done by parastatal organisations such as Agricultural Development Agency (ADA) (ADA, 2023).

The second issue was the pollution status of the water resources since most water bodies are contaminated with disposed waste materials such as nappies. In this regard, it is imperative to test the water and assess it for irrigation suitability with regards to pathogens and other pollutants. The Decision Support System (DSS) developed by du Plessis et al. (2017) can be used. If the identified contaminants emanate from households, this could be due to lack of awareness on waste management practices as discussed by Cofie et al. (2016). This can be prevented by education and awareness programs for safe management of household waste. Communities need awareness on the impact of poor waste management on public health, the environment and biodiversity. The same idea have worked well on urine recovery in eThekwini whereby positive attitude on collection and handling the urine resulted from proper community education (Etter et al., 2015). In cases where boreholes are installed presence of pathogens in groundwater might be caused by unproperly managed pit latrines which are predominant especially in rural areas (Back et al., 2018; Masindi and Foteinis, 2021; Ngasala et al., 2019). This can be addressed through safe collection, treatment and valorisation of faecal sludge using technologies such as pyrolysis into biochar (Mamera et al., 2021).

The rural farmers do not have access to profitable markets. They cannot produce enough to meet demands for reliable supply to supermarkets, contract farming and fresh produce markets. Lack of access to profitable markets is common to South Africa small scale farmers as explained by Selepe et al. (2014). As a result they are outcompeted by established commercial growers because most small-scale farmers operate in silos. According to the participants, they only produce various vegetables for local markets such as spaza shops, neighbourhood and the community social grant centres. Access to lucrative markets needs good linkages and consistent supply of good quality products. This is possible if farmers could organise themselves into coalitions, strengthen good internal and external relations with group members and market chain actors (Kaganzi et al., 2009). Therefore, organising the identified cooperatives, creating strong relationship with various stakeholders (microfinances, governmental, retailers/processing companies and academia) may provide a platform in which farmers can financially and technically capacitate themselves and, gain good market linkages for sustainable businesses. Otherwise, they may continue operating as subsistence farmers. This will negatively market CBE interventions as part of improving livelihoods in alignment with expected outcomes of the project.

3.3.2.2 Appelsbosch farmers case study

Working collaboratively with institutions that have reliable land for example hospitals, prisons, churches and schools was considered during the study period. About 17 ha of potentially arable land owned by the Lutheran church leased to KZNCC was identified at Appelsbosch. According to a key informant from the KZNCC there is a signed MOU with the Ubuhlebemvelo

(UB) cooperative to use the land. The UB cooperative is headed by three women from the local community in Appelsbosch. At that moment the cooperative was operating five greenhouses for tomato production. The land owned by a church council is also equipped with a water reservoir and the whole 17 ha provides an opportunity to scale out production of processable agriproducts (Figure 3.9).

According to the key informant the farmers are using commercial fertilisers for horticultural production. As noted in the FGD with Vulindlela women group (Section 3.3.2.1), soil analyses are not being done, all the fertilisers are applied based on established fertigation program. The farm seemed to be an established and organised commercial entity which follow spraying, fertiliser application and irrigation programs. This is different to the women cooperatives identified in Vulindlela. Who, like most communal farmers, are having problems in purchasing agrochemicals including fertilisers. Meaning that the UB cooperative has the potential commercial capacity and expertise to drive a sustainable CBE. However, they were not applying fertilisers based on crop requirements and residual fertility as suggested in the practical guideline (Odindo et al., 2022b). Just like the previous Vulindlela community they need training on soil testing and analysis.

After understanding the concept of CBE the UB cooperative bought in the idea and committed to support resource recovery and reuse using co-compost. The Appelsbosch farm had advantages over the Vulindlela site. The farm complies with the Department of Water and Sanitation (DWS) National Water Act licence for crop irrigation (DWS, 2022).They were producing horticultural crops using irrigation water from a perennial water stream joined to the catchment area (Figure 3.9). In addition, there was a water reservoir constructed by the Lutheran church to support community agriculture. However, according to the key informant the reservoir was vandalised, the metal barricades where also stolen and became a public hazard since the children where prone to drowning risks. For safety reasons the reservoir was not being used and closed. Theft of agricultural infrastructure is one of the social ills common in South Africa (Roberts and Shackleton, 2018). In addition to infrastructural theft, the key informant was concerned about agricultural products. The key informant suggested different strategies to manage and prevent theft. These include minimising the use metal in infrastructure by for example using plastic irrigation pipes than metal pipes. Some crops such as tomato, butternuts and Swiss chard are at high risk because they are consumed in most households. Crops such cauliflower, cucumbers and broccoli has been singled out as less risk because they are less common to community members. Integrated approaches such as involving local communities in skills development programs and increased awareness campaigns that may help create a sense of ownership and stimulate protection of such infrastructure from vandalism and theft have been suggested by the key informant.

Figure 3.9. An aerial view of the Appelsbosch agricultural centre.

Lack of financial compliance and skills to apply for support funding are some of the challenges brought by the Vulindlela women group and the Appelsbosch farmers. They do not have proper paperwork; business accounts, tax and organisation registration to comply with microfinances requirements for accessing a loan. Although the organisation once benefited from the Department of Agriculture through access to vouchers for purchasing inputs but they could not meet the requirements of the support initiatives such as the Recycling Enterprise Support Program (RESP) from the Department of Environment, Forestry and Fisheries (DFFE) (DFFE, 2019). This is not odd, a review by Zantsi (2021) reported that most cooperatives are likely to fail due to lack of organisational structure, skilled human capacity, lack of knowledge on agricultural diversity and limited capital. However, the UB cooperative managed to benefit from Industrial Development Council (IDC) which funded construction of the five greenhouses on the site. The funding was applied for them on their behalf but this is no longer possible. The government stopped accepting applications made on behalf of other individuals. Therefore, knowledge and raising awareness on complying with financial laws should be included in programs supporting community capacity building as suggested by Zantsi (2021).

Labour shortage is one of the challenges hindering them to operate to maximal capacity and the same have been identified from farmers in Vulindlela. In a country battling with unemployment there is an opportunity to source labour from communities but according to the key informant they do not have financial capacity to employ extra labour during peak periods. The UB cooperative does not employ any human personnel, they work on their own and share dividends after sales. In a move to support production of scale, the key informant suggested that community mobilisation, integrating training with production whereby unemployed youth or trainees may help during peak periods could be an option.

According to the key informant there are lots of markets available for them to sell their produce. These markets include fresh markets such as Durban fresh produce market, Mkhondeni fresh market, Dalton Spar, Tshala Nathi enterprises, Appelsbosch hospital, Appelsbosch Tvet college, Bamshela Boxer, Fresca fruit and veg and Super Saver markets. However, just like other cooperatives they face challenges in meeting quantities for market demands and continuous supply. The other issue brought forward was post-harvest losses which were extensive for tomatoes. However, the key informant supported the idea of agro-processing tomato into chilli sauce. In this regard, the UKZN proposed collaborative efforts with other stakeholders to establish robust small-scale processing technologies for making tomato paste, tomato sauce and chilli powder and much of these is detailed in Chapter 7.

3.3.2.3 Sobantu cooperatives case study

The rich picture exercise on agricultural production systems context is shown in Figure 3.10. The diagram presented information from two study groups because majority of the participants arrived a bit later after the exercise has commenced. The third group was later formed during preceding sessions.

The major problems identified by the farmers were lack of irrigation infrastructure, agricultural equipment, storage facilities, security, input costs (especially seedlings, pesticides and herbicides), soil analysis, understanding the best practices for using organic manure for example compost, transport cost and markets. The same challenges were highlighted by farmers from Appelsbosch during a meeting as well as during the Focus Group Discussion (FGD) done in Vulindlela (Section 3.3.2.1). These challenges have been reported in literature from other countries such as Ethiopia (Halos-Kim, 2013).

Agricultural production systems in South Africa are dominated by commercial farming and the marginalised group practice subsistence farming and hardly afford machinery and equipment (Adey et al., 2004). The target farmers are resource constrained hence cannot produce to nourish their agribusiness while dealing with household income. The potential returns from investing in agribusiness infrastructure was well explained by Maru et al. (2023) based on Ethiopian experience. Meaning that infrastructural development is one of then considerations in co-creation of resilient food systems incorporating CBE principles.

The current paradigms have been shifted towards agroecology in development of resource efficient environmentally sustainable food systems (Wezel et al., 2020). In this instance, the farmers showed some knowledge and understanding of the need to analyse soils prior to fertiliser application as a way of saving on input costs. However, an argument by Pettersson and Wikstrom (2016) revealed that Sub Saharan Africa is currently not using enough fertilisers to meet expected quantities. In addition, the authors mentioned that the human excreta fertilisers may only supplement approximately one fifth of the total fertiliser requirements. Thus, within the current context, it is imperative to establish strategies to promote meeting fertiliser demands prior to supplementing with HEDFs. This is a blessing in disguise, the fertiliser market demand is practically very high but affordability might be an issue as brought up during the FGD.

Availability, access and understanding market dynamics is one of the major limiting factors prohibiting small scale farmers and this has been a case of concern in the Sub Saharan region (Mburu and Massimo, 2005). This confirm that dynamics such as distance to the market and their availability might be a problem. However, during a meeting with farmers in Appelsbosch, markets are not a problem, but according to them, major challenge is the costs of inputs such as agrochemicals.

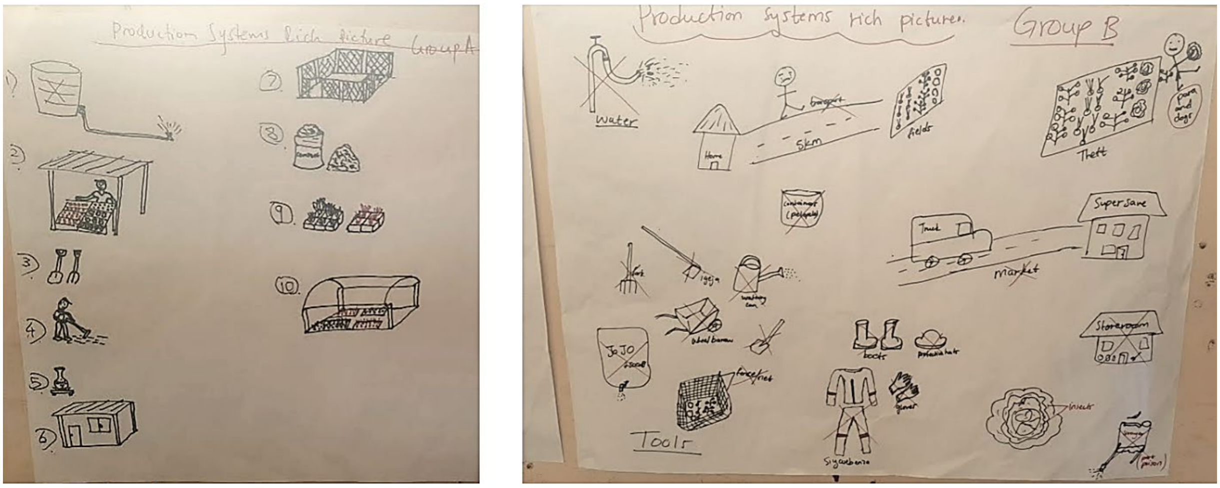

Figure 3.10. A rich picture illustrating the current state of agricultural production systems within the identified target groups (Group A and B).

Expectations in food systems changes in response to CBE interventions as envisioned by the farmers are shown in rich picture diagrams (Figure 3.11). In this case all the farmers mentioned co-compost as their intervention despite having other innovations such as urine derived fertilisers and treated wastewater. This is because the target farmers are part of the RUNRES transdisciplinary innovation platform and they have learnt, appreciated and understood the agricultural use of human excreta derived co-compost. In addition the literature has proved that there is positive acceptability in the use of HEDFs by farmers within Msunduzi (Gwara et al., 2023; Wilde et al., 2019).

The farmers expect CBE interventions to improve their livelihoods and capacity to invest in agribusiness (Figure 3.11). Sometimes benefits of using interventions such as co-compost might not be immediate compared to inorganic fertilisers. Benefits associated with co-compost include improved soil properties such as nutrient and water retention, fertiliser use efficiency and soil biodiversity (Fendel et al., 2022). This information should be known by farmers, hence awareness programs and training on CBE must be considered and implemented. However, convincing farmers to use HEDFs is not an easy task as farmers are likely to give up for some income generation opportunities. Farmers should be incentivised through for example by linking them to lucrative markets which generate more income for them to focus.

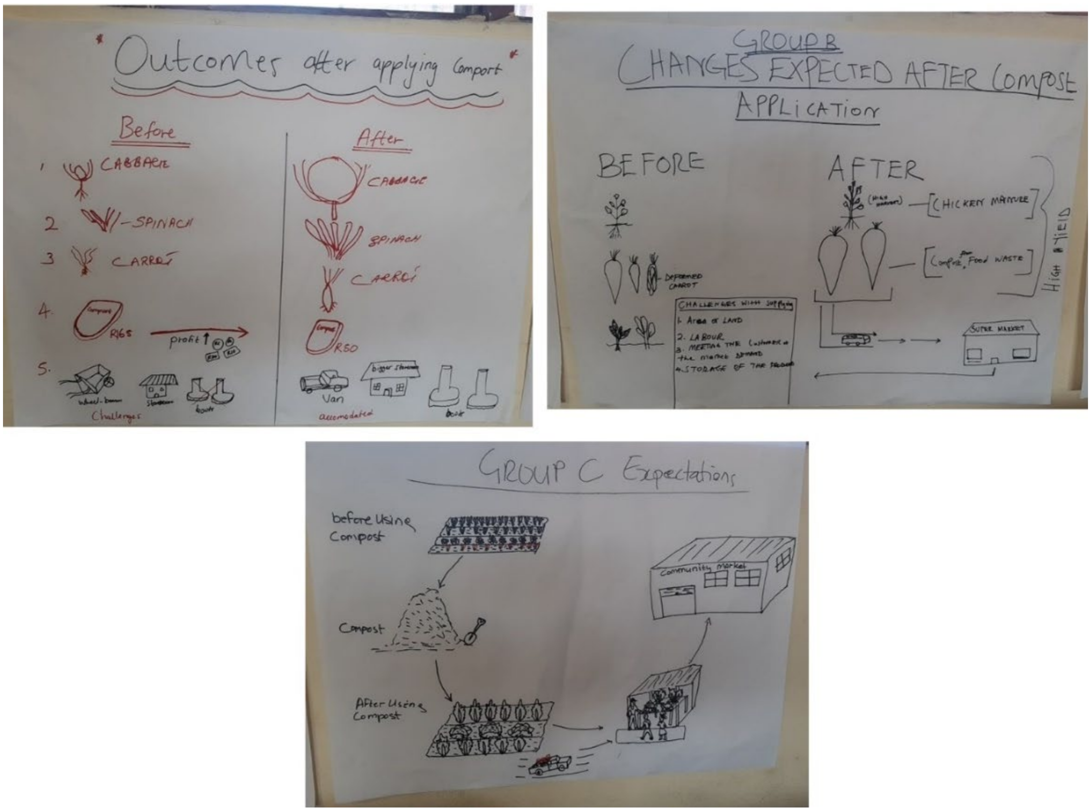

Figure 3.11. Envisioned changes in Sobantu small scale farmers' food system with circular bioeconomy interventions.

3.3.2.4 Bishopstowe farmers

During interactions with NCEDA, the organisation showed some positive attitudes on integrating innovative solutions to improve food production in communities. This aligns with the project outcomes and expected impacts of fostering community development by encouraging the use of low-cost solutions such as HEDFs as alternatives to inorganic fertilisers by practically including green solutions characterised by low carbon footprint in the production systems. For example the current inorganic phosphorus fertilisers manufacturing process uses non-renewable materials and the Haber Bosch process for nitrogen fertilisers is energy intensive and characterised by high C footprint (Pathy et al., 2021). Meaning that NCEDA and KZNCC also provided a platform to improvise climate change mitigation strategies while addressing food insecurity.

Several challenges that may hinder transitioning to a CBE have been identified after engagement with the women cooperative from Vulindlela (Section 3.3.1.1). However, the project team engaged NCEDA with such issues in mind. The NCEDA and its partners could address such challenges by forming a Food Collective Groups (FCG) to (i) coordinate and share consciousness and collective action through workshops, trainings, co-created spaces and linkages, (ii) establishment of cooperatives from churches and marginalised communities, (iii) facilitate collaborations between various cooperatives and strategic partners. The NCEDA is also envisioning the co-creation of agroecological hubs and organic farming with the UKZN. This enables sustainable agricultural practices though access to expertise and knowledge, capacity building within the network and localised profitable food production. In addition, these practices should be assessed and provided as evidence-based information to speed up policy change on handling HEDFs.

Some other identified cooperatives working with NCEDA were Sobantu, Mfenendala, Sakhubuntu and Tholulwazi. Each cooperative has different interests; Sobantu produces cabbages, Mfenendala is into poultry production and they expect to grow crops and herbs, Sakhubuntu is focusing on garlic, chillies and green pepper for processing and Tholulwazi is focusing on sheep and poultry production (Figure 3.12).

Figure 3.12. Current activities at Bishopstowe Agricultural Living Lab showing poultry activities by Thlulwazi cooperative (A), Mfenendala traditional chicken (B), plant biodiversity conservation of local pumpkin seeds (C) and cabbage production by Sobantu cooperative (D).

As a result of such a coalition, the project team in collaboration with other stakeholders and the cooperatives established an agroecological hub named Bishopstowe Agricultural Living

Lab (BALL). The agroecological concept is a broader approach, which according to the Food and Agricultural Organisation (FAO), use ten approaches to establish resilient food systems in cognisance of environmental integrity, social inclusion, biodiversity protection and economic development (Barrios et al., 2020). The agroecological hub is being used as a testing site for CBE interventions, agro-processing, agricultural skills development and biodiversity protection and preservation. Currently, the project has established activities such as co-composting, ecological sanitation and urine valorisation and agricultural use of other human excreta-based fertilisers (Figure 3.13). Faecal sludge emptying from pit latrines is a common challenge in South African communities and other African countries served by pit latrines (Mamera et al., 2021). This contaminates groundwater resources thereby contributing to outbreaks of waterborne diseases. Therefore, safe collection and treatment of faecal sludge using technologies such as co-composting for agricultural has been included and implemented at the BALL. However, co-composting could not proceed during the project period. The group that was supposed to do composting did not commit despite showing enthusiasm. As discussed in Section 3.3.2.3 several interventions may motivate farmers to commit, for example awareness on indirect benefits such as public health protection and business strategies to earn more profits through for example value addition.

Figure 3.13. Circular economy initiatives implemented at BALL showing storage tanks for urine to be collected from ecological sanitation system to be constructed at the site (A), wood chips and faecal sludge collected in blue containers for co-composting (B) and faecal sludge emptying at Julukandoda primary school (C).

3.3.3 Stakeholder identification, characterization, and identification of synergies

The cooperatives have identified several challenges affecting their existing agricultural systems and their potential mitigation strategies. Moving forward, the stakeholders that may assist with solutions to challenges affecting the successful implementation of profitable small-scale agro-processing entity identified by women owned cooperatives have been identified in Table 3.2.

Table 3.2: Justification for selecting various stakeholders across waste and food value chains. Stakeholders in unshaded boxes needs to be engaged.

Stakeholder category	Stakeholder	Justification
Statutory agency	Umgeni water	Regulate safe sanitation services and waste management
Local government	EWS, uMsunduzi municipality	Provides safe sanitation and waste management
Government department	Department of Agriculture, Land Reform and Rural Development (DALRRD)	Fertiliser registration regulatory body
Statutory agency	Consumer Goods Council of South Africa (CGSA)	Consumer protection
Government department	Department of Health (DOH)	Ensures equitable, sustainable, and efficient access to health and prevention of illnesses to the public
Statutory agency	South African Bureau of Standards (SABS)	The national standardization institution in South Africa
Government department	Department of Trade, Industry and Competition (DTIC)	Promotes decent work outcomes (more jobs as well as better jobs), industrialization, equitable and inclusive growth, and social inclusion
Government department	Department of Women Youth and Persons with Disabilities (DWYPD)	to accelerate socio-economic transformation and implementation of the empowerment and participation of women, youth, and persons with disabilities through oversight, monitoring, evaluation and influencing policy.
Farmers	Sobantu cooperative Elite crop (Pinetown)	Potential to use HEDFs in agricultural fields or consume resulting food products
Processors	Fresh chips producers in Sobantu	Small scale processing potential
Retailers	Spar, Pick n Pay, Shoprite, Florists and garden centers	Potential markets for food/nonfood products grown using HEDFS and fertilizers
Consumers	Community members	People with potential of consuming or utilizing food/nonfood products from HEDFs
Sanitation technologies specialists (Containment) Waste recyclers (Collection)	WASH Envirosan PID – pit emptying Local recyclers	Perspectives on best resource recovery Pit emptying and other waste management techniques
Human excreta treatment specialists (Treatment)	DEWATS EWS/Umea/ PSS/WASH	Human excreta valorization expertise.

3.3.3.1 Private sector

Stakeholders across the food value chain are also important, especially small- and large-scale local input suppliers, which have potential to deal with HEDFs. Although, the existing South African guidelines and regulatory structures are not prohibitive on the use of HEDFs, acceptance by retailers is not well understood, therefore four of the major food retailers (Spar, Pick n Pay, Woolworth and Checkers) and other non-food retailers such as floral companies and in nurseries may play a role in transforming their food supply chains in cognizance of the CBE interventions. There is great potential for small scale farmers to elevate lucrative business if adequate support is provided. A Pinetown based women owned agribusiness entity, Elite group produces horticultural crops for both local and international markets, is an example of a successful company. The company benefited from agribusiness support initiatives by the Agricultural Development Agency (ADA). The agency support upliftment of small emerging agribusinesses owned by marginalized groups across the whole chains through partnerships, capacity building and financial support (ADA, 2023). Bringing these successful emerging commercial farmers into the dialogue and transdisciplinary platform boost confidence for the other cooperatives.

3.3.3.2 Governmental institutions

Small scale farmers are generally financial constrained to purchase machinery and operate farms. They need developmental loans to operate sustainably. Some of the options include green funding from governmental institutions. The Department of Forestry, Fisheries and Environment, (DFFE) has funding programs to promote greening projects in support of poverty eradication and sustainable development, which in this case, transitioning to a CBE in pursuit of pleasant environment for current and future generation (DFFE, 2020b).

Clear policies and legislation regulating the use of HEDFs for food crop production remains a major constraint. A global perspective the use of human excreta is not a problem as evidenced in countries such as Kenya (Moya et al., 2019a) and Sweden (Vuna, 2022). However, institutions such as Umgeni water, DFFE and Department of Water and Sanitation (DWS) directly govern sanitation management, human excreta management practices and resource recovery. They play a role in implementing policies that directly allow farmers to produce and sell food products made using HEDFs. For example, the DWS developed national sanitation strategies in alignment with the National Environmental Management Act of 2008 (NEMA) to promote sustainable waste management to protect the environment from pollution (DFFE, 2020b). Although not directly linked to sanitation, other governmental organs may play a pivotal role in driving CBE interventions. The Department of Health laws such as the Foodstuffs, Cosmetics and Disinfectants Act of 1972 which ensures safety for consumers of any food products (DOH, 2023). The Occupational Health legislation applies to protect health workers across the value chain in alignment with the WHO sanitation safety plan (WHO, 2016).

The South African Department of Agriculture Rural and Development (DALRRD) core business is to provide equitable access to land, integrated rural development, sustainable agriculture, and food security through transformed land ownership dynamics, promotion of sustainable livelihoods, innovative sustainable agriculture, promotion of access to opportunities for vulnerable groups such women and unemployed youths (DALRRD, 2022a). The DALRRD may provide information and/or assistance on potential and available incentives that may promote sustainable agricultural development in low-income farms for example: extension services, machinery and equipment hire, financing, market search, value addition, contract farming, government subsidies, agro-processing advisory service (food quality, export and imports, etc.). Furthermore, more information on regulatory issues for registering and utilisation of HEDFs such as urine and derived products, e.g. the Fertilizer, Farm Feeds Act (1947) is regulated by the DALRRD. The DALRRD may play a role in the establishment of policies that explicitly allow the use of HEDFs for food crops. The department has other programs that promote small scale agro-processing, and these include the Comprehensive Agricultural Support Programs (CASP) agro-processing infrastructure development programs (Nesamvuni et al., 2016).

The identified cooperatives are aspiring to establish profitable and sustainable enterprises, which have direct impact on all actor across the value chains. The Department of Trade, Industry and Competition (DTIC) was identified as relevant due to its responsibility in promoting structural transformation to cope up with dynamic industrial and global economic competitiveness, providing a conducive environment for investment, trade and enterprise development, coordination of governmental institutions towards economic development and improvement of economic development policies (DTIC, 2023). The DTIC provides information on available or potential local, regional, or international markets for specific waste-based products, regulations arounds such markets or channels for unlocking related regulatory and legal economic development barriers. Furthermore, the DTIC, together with the Department of Women Youth and Persons with Disabilities (DWYPD), may provide potential and available governmental incentives, micro financial support and development programs for youth, women and disabled groups in a social inclusive manner.

From the governmental perspective, there are laws, regulations and responsibilities by different departments which might support policies on the agricultural use of HEDFs. Coalition of governmental departments is needed in drafting the policies allowing direct use of HEDFs for food crops.

3.3.3.3 Local municipalities

Local municipalities are constrained with providing adequate sanitation and solid waste management within their areas of jurisdiction (Msunduzi municipality, 2015). They need sustainable and innovative waste management strategies. In this regard, some municipalities, for example uMsunduzi launched several projects to promote green economies, e.g. Wildlands tree for life projects in Greater Edendale and urban agriculture projects around the Baynespruit. They had plans to create markets for trees and ornamentals in their urban beautification programs using seedlings produced using treated wastewater and faecal sludge co-compost. The eThekwini municipality agroecology department is currently providing training and market access information for farmers. Therefore, integrating local municipalities in CBE can aid capacity building and co-creation of sustainable markets.

3.3.3.4 Research and innovation institutions

There are several documented technologies to treat different excreta streams (wastewater, urine, and fecal sludge). Literature has unveiled that the major limitation to unrestricted use of DEWATS effluent is pathogen loads, despite planted gravel filter treatment (Musazura and Odindo, 2022). Therefore, the technical and economic feasibility of integrating other advanced wastewater treatment technologies such as activated carbon, ozonation and UV radiation in low-income communities needs to be assessed. Most of these technologies have been tested in laboratory scenarios and their practically applicability at large scale have been found likely to be difficult for low income scenarios (USEPA, 2012). Wastewater treatment companies may provide an insight on the best treatment technology. The UMEA university has experience in existing urine treatment technologies in terms of costs, technically efficiency in nutrient recovery, smell reduction and stability, volume reduction and CEC, potential future technologies, and issues to consider for implementing such technologies. They play a role in research and development by supplying materials for testing.

Acquiring feedstock for activities such as co-composting needs proper planning. There are several actors who have experience in practical engagements with communities where pit latrines are located. Some private emptying companies have been identified as crucial in the list of stakeholders. The academic institutions such as WASH R&D are into sanitation research and have a better understanding of community dynamics around acquiring fecal sludge.

3.3.3.5 Regulatory bodies

Compliance watch dog is important to ensure that laws are forced. The South African Bureau of Standards (SABS) and Consumer Goods Council of South Africa (CGSA) are important watchdogs. The CGSA is responsible for advocacy, lobbying, engagement and collaboration on non-competitive industry matters, sharing of best practice standards, provision of regulatory and advisory services and access to a hub of valuable industry insights. This department might provide adequate direction for the farmers to leverage development funding, market opportunities and guidance to operate within the legal boundaries.

3.4 Conclusions

- The project identified and engaged the women and youth owned cooperatives from Vulindlela, Appelsbosch and Sobantu communities.
- Challenges affecting existing agricultural systems in the identified women owned group included land tenure issue, financial and technical constraints to run viable agribusiness projects, lack of information on value addition and reliable markets.
- Waste and food value chain stakeholders important for a successful implementation of a legal, acceptable, viable and safe innovative solutions have been identified and characterised as regulatory boards (SABS, CGSA), governmental institutions (DALRRD, DFFE, DWS, DTIC, DWYPD, DOH), private entities (Commercial farmers, Retailers) and local municipalities (Msunduzi municipality).
- The roadmap for collaborative research with the identified communities and stakeholders was established. The major focus of the project was testing HEDFs from different innovations on selected crops, production of co-compost using VIP sludge mixed with green waste, improvement of DEWATS wastewater treatment through integration of advanced methods, proposition, assessment, and implementation of sustainable small scale processing entities for identified cooperatives and urine treatment at the identified school.

3.4.1 Recommendations

- Mitigation strategies to challenges faced by small scale farmers were provision of agribusiness management training to cooperatives, linking them to sound and viable local and international markets, incorporation of value addition practices in their farming systems and leveraging funding from different institutions such as governmental incentives and other microfinances.

3.4.2 Challenges and lessons learnt.

- Local communities were enthusiastic about the use of HEDFs but active participation was affected by gatekeeper interests and incentives or pull factors to attract them invest in CBE interventions.

- Farmers could hardly meet due to Covid 19 restrictions, based on experience encountered, digital tools such as WhatsApp groups may be used for communications amongst cooperative members.
- Interactions with governmental departments was unfruitful so their views could not be brought on to the table. Active participation of governmental departments is crucial in promoting policies clarifying the use of HEDFs for food crops.
- Theft and security are serious issues that may prevent active participation of private companies and small-scale farmers in local communities.

4 ADVANCED TREATMENT TECHNOLOGIES

4.1 Introduction

Although there are several benefits for using agricultural use of HEDFs, one limitation includes the perceived human health risks. It is imperative to maximise on benefits associated therewith while reducing health risks. The previous project (WRC K5/2777) established a practical guideline on sustainable agricultural use of various human excreta streams derived fertilisers (Odindo et al., 2022b). The guideline incorporated the WHO Sanitation Safety Plan (SSP), which is a stepwise multibarrier approach to protect vulnerable groups across the sanitation and food value chain. The guideline did not comprehensively address the removal of micropollutants from wastewater and or pathogens to meet standards for unrestricted agricultural use. Even some farmers in countries like Ghana are not practicing safe agricultural production practices although they are educated and trained on sanitation hygiene (Drechsel et al., 2014). Therefore, to protect the public, workers and consumers, human excreta should be thoroughly treated to meet standards for unrestricted agricultural use. Some technologies such as latrine dehydration and pasteurisation (LaDePa) have been used to eliminate pathogens from faecal sludge (Septien et al., 2018). The DEWATS does not remove all pathogens to meet standards for unrestricted agricultural use. Although there are several advanced technologies such as ozonation, UV radiation and chemicals for wastewater post treatment, and the use of carbon rich adsorbents such as activated biochar to remove organic micropollutants, these technologies have not yet been incorporated in DEWATS treatment.

The project is working synergistically with the RUNRES innovation platform and innovations to test the applicability of sanitation-based innovations in South African communities. However, some of the technologies supporting the project (DEWATS and biochar plant) could not be established in the targeted community due to community challenges experienced (Section 3.4.2). After consultation with stakeholders the approach to the study was revised. The team considered readily established sanitation technologies in parallel to those being established under the RUNRES project. Therefore, the study assessed the application of advanced treatment technologies in improving the safety of human excreta derived fertilisers for the production of food crops with focus on; (i) engaging with stakeholders relevant to application of advanced technologies that can be used to treat human excreta, (ii) apply advanced waste treatment methods in human excreta materials, monitoring and evaluating the flows of micropollutants and pathogens across the sanitation and food value chains.

4.2 Human excreta treatment for public health safety in identified innovations

4.2.1 Approaches

All the innovations in which the project operated were mapped. The potential health risks emanating from each innovation were identified. The respective treatment and interventions to minimise risks and stakeholder required were identified in consultation with stakeholders. The multi barrier approaches required to deal with each risk were discussed.

4.2.2 Results and discussion

The sanitation and food systems sanitation safety plan flow diagram showing risks across the respective value chains and interventions required to eliminate organic pollutants and pathogens is reported in Figure 4.1. The DEWATS has four treatment modules ending up with Planted Gravel Filters (PGF). Previous studies including a literature review with metanalyses showed that the DEWATS does not eliminate all pathogens even after PGFs (Musazura and Odindo, 2022). Advanced treatment methods such as ozonation are recommended to further treat the effluent to standards for unrestricted agricultural use. The PCD3 (Figure 4.1) refers to advanced treatment using ozonation or ultraviolet lamps. The ozonolysis has intertwining abilities to remove organic pollutants as well as pathogens making the effluent safe for unrestricted agricultural use (Kim and Tanaka, 2009). The PSS2 refers to DEWATS installation being done at Julukandoda primary school (Figure 4.1).

The wastewater treatment is not limited to effluent from the DEWATS. Figure 4.1 shows that there is potential for borehole water contamination due to unsafely managed pit latrines as shown at point TPL2. South Africa is a country with more that 30% population being served by pit latrines and the identified study communities are facing challenges with full pit latrines. Full pit latrines are problematic even in other countries where they are major sources of well and borehole water contamination (Back et al., 2018; Masindi and Foteinis, 2021; Ngasala et al., 2019). The proposed agricultural use of wastewater or partially treated human excreta may also cause public health risks through drainage percolation (TCD4). Even if not and the common channel of discharging wastewater into water bodies (TCD3) might have problems downstream. It is therefore vital that the wastewater or even freshwater from boreholes and rivers must be monitored for pathogen and organic pollutants prior to use. In cases where the standards for unrestricted agricultural are not being met further interventions such as ozonolysis and UV may be considered (Peyrelasse et al., 2022). Low-cost bio adsorbent materials such as biochar are used to remove organic pollutants (Kaetzl et al., 2019; Khan et al., 2021; Nkomo et al., 2021).

The major treatment points for faecal sludge are PPL4 and PPL5. One of the advanced faecal sludge/biosolid treatment technology include latrine pasteurisation and dehydration (LaDePa) to produce sterile pellets used as soil conditioners (Septien et al., 2018). Despite being a mostly recommended method in total pathogen elimination and sludge stabilisation, the method is expensive and might not be economically sustainable in low-income communities (Harrison and Wilson, 2012). Therefore less technical demanding technologies that may be potentially implemented include pyrolysis and co-composting. Co-composting involve thermophilic aerobic degradation of organics to temperatures that sterilises faecal sludge while stabilising the products (Cofie et al., 2016).

The urine stream treatment starts from point PF4. The best advanced treatment method which have led to the development of currently marketed Aurin, which is even used for food crops, is nitrification and distillation process (Etter et al., 2015). The method is highly technical and might be difficult to implement in low-income communities. Some other technologies such as struvite production, urine storage and solar treatment can be applied to sterilise urine. The urine carries all the metabolic waste from human body including pharmaceuticals and these can be removed by nitrification and distillation processes. It is further intriguing that simple methods such as urine storage for at least 2 months and the use of powdered activated carbon can eliminate significant concentrations of pharmaceuticals down to a risk quotient of 1 (Özel Duygan et al., 2021).

As a result waste treatment processes such as pyrolysis (PPL5) of organic green waste, which is imposing excessive landfill maintenance costs to municipalities and the vast faecal sludge/biosolids piling up in hazardous landfills (Abdel-Shafy and Mansour, 2018) may be integrated with wastewater treatment (PCD3), urine treatment (PF4) and even treatment of other freshwater streams (TCD3, TCD4 and TPL2).

The project team required to complete advanced waste treatment methods for further improving human excreta quality for safe agricultural use was assembled. The Watermed (PTY) and some RUNRES partners were identified as partnering private organisation whose focuses are to treat wastewater and faecal sludge respectively.

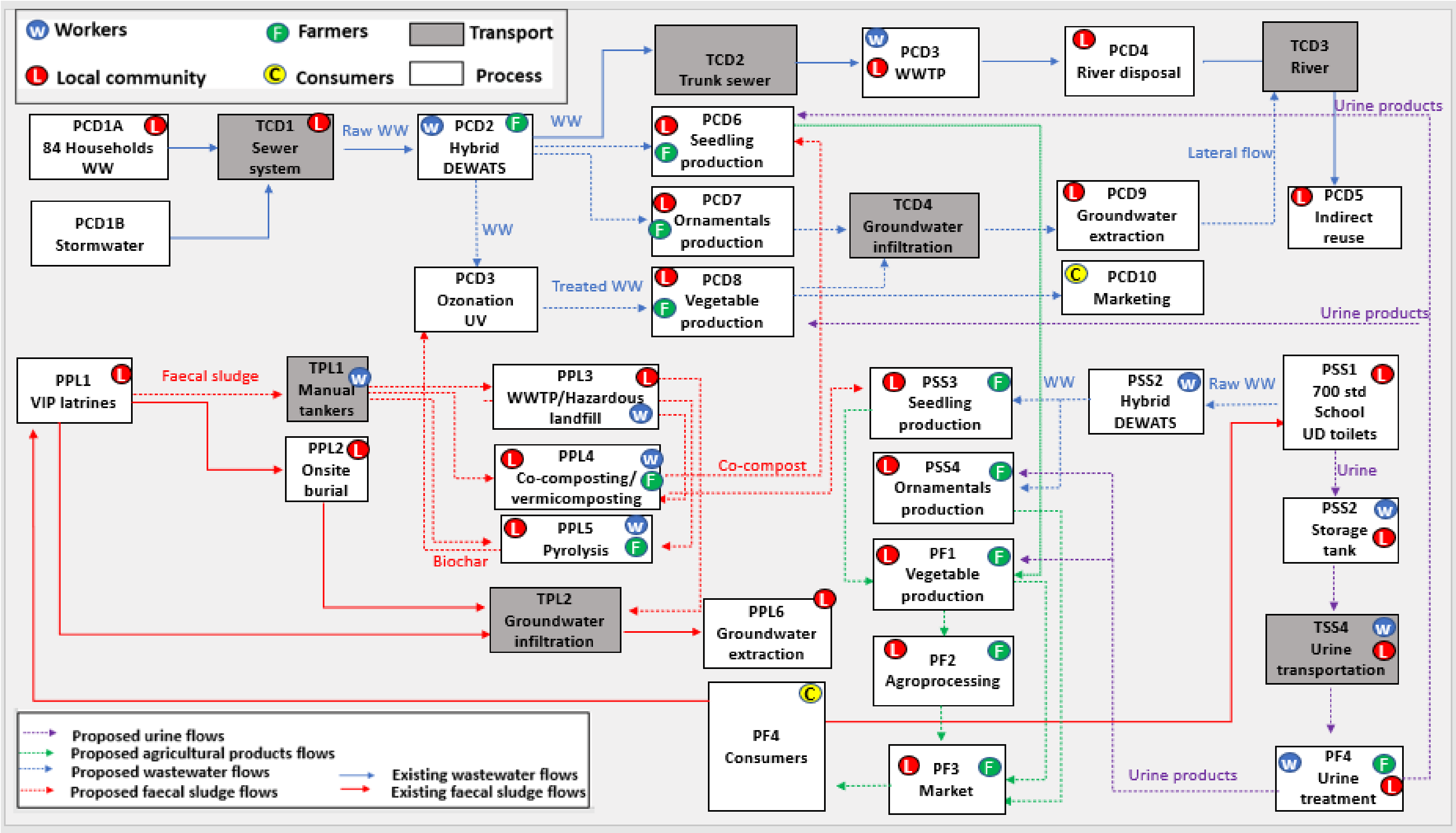

Figure 4.1. The established sanitation safety diagram within the study boundary, arrows showing the assumed flows of human excreta streams (wastewater, urine and faecal sludge), linkages between innovations and identified risk areas that needs treatment interventions.

4.3 Pathogen Reduction in Municipal Anaerobic Filter Effluent Using Advanced Oxidation Processes for Unrestricted Crop Production.

4.3.1 Introduction

Ozonolysis involves using Ozone (O_3), a gas with a pungent smell and moderate water solubility (110 mg/L at 25°C) (Travaini et al., 2016). The reactive O_3 (E = 2.07 V at 25 ° C) can be generated from air/oxygen via a high-voltage corona discharge process. Due to its molecular electronic configuration, which makes it unstable, ozone, once dissolved in water, self-decomposes and undergoes oxidation reactions, leading to the disinfection of micropollutants (Zhang et al., 2023). On the other hand, UV photolysis works by a mechanism of bond breaking; organic molecules absorb UV light, creating highly reactive free radicals that break the chemical bonds that keep the organic molecules together (Kim and Tanaka, 2009). Photocatalyst TiO_2 nanoparticle is a semiconductor bearing electrons on the valence band. With the help of UV light, enough energy is supplied capable of surmounting the bandgap energy, leading to the movement of electrons to the conduction band. This creates an electric current that ionizes water to form Reactive Oxygen Species (ROS) like the hydroxyl, Superoxide, and peroxide radicals that degrade most organic and inorganic contaminants (Al-Mamun et al., 2019; Kowsari, 2017).

Constructed and natural wetlands take up much space, making the DEWATS technology expensive due to land acquisition (Sibooli, 2013). DEWATS' practicality as an onsite treatment solution is also limited since the effluent does not meet the reuse standards (Arumugam et al., 2023). By treating the primary effluent, DEWATS can replace septic tanks as an onsite treatment alternative for densely populated municipalities, institutions, and schools. This study preliminarily evaluated the application of UV light photolysis, photocatalysis, and ozonolysis to treat primary DEWATS effluents to remove organic micro-pollutants and pathogens. The main parameters of interest included UV absorbance (UV254), biochemical oxygen demand (BOD), dissolved organic carbon (DOC), pH, turbidity, *Escherichia coli*, and Total coliforms.

4.3.2 Materials and equipment

Reals DEWATS effluents (primary and secondary) were sourced from the local plant in Durban and stored at 4°C. The primary effluent was collected after the aerobic/anoxic/anaerobic stage, while the secondary effluent was collected after the wetlands.

4.3.2.1 Ozonolysis experiments

The ozonolysis experiment, Figure 4.2(a), was carried out in an ozone reactor of 4 L capacity at an ozone dosage of 90 mg per minute. Ozone gas was generated from the air (source of oxygen) using an ozone generator coupled to an air compressor, then bubbled through DWW from the bottom via a gas diffuser. The exhaust gas from the reactor was passed through a potassium iodide (KI) solution to destroy unreacted ozone.

A 2-litre UV-Vis photoreactor was connected to a peristaltic pump for feeding, and fluidization was used for photolysis and photocatalysis (Yusoff et al., 2018). During photolysis, 2 L of the AF effluent was pumped into the reactor and then subjected to photolysis. For TiO_2 photocatalysis, 1 g of TiO_2 nanoparticles was added per litre of the effluent and allowed to fully mix for 30 minutes. After that, the substrate was transferred to the UV reactor for photocatalytic treatment. A schematic representation of the photolysis and photocatalytic unit is given in Figure 4.2(b). During the AOP treatments, samples were withdrawn at predetermined time intervals and analysed.

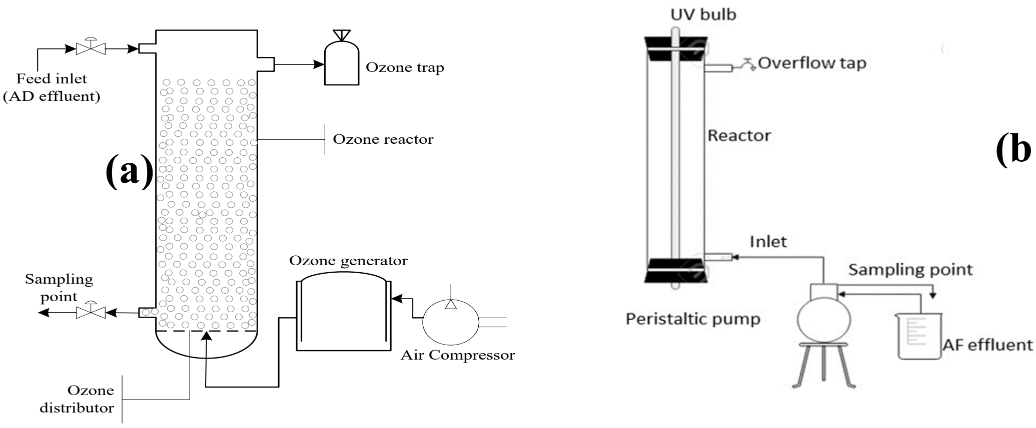

Figure 4.2. Schematic representation of (a) ozonolysis and (b) UV photolysis and TiO2 photocatalysis unit.

4.3.2.2 Chemical analysis

Initial and final samples after every experimental run were analysed for pH, dissolved organic carbon (DOC), biochemical oxygen demand (BOD), turbidity, *E. coli*, and Total coliforms as per the standard methods of analysis (APHA-AWWA-WEF 2005). UV-Vis absorption spectroscopic analysis was done at a maximum absorption wavelength of 254 nm (Otieno et al. 2018; Batista et al. 2015). Samples with absorbance measurements above the range (>9.99) were serially diluted until the absorbance could be determined. A titrimetric method determined the ozone concentration using a potassium iodide (KI) solution (Venkatesh et al. 2015; Otieno and Apollo 2021).

4.3.3 Results and Discussion

4.3.3.1 Change in DOC/ BOD/ Humics

DOC levels increased from 3.4 mg/l to 12.8 mg/l, 7.9 mg/l, and 6.6 mg/l after ozonolysis, UV photolysis, and TiO_2 photocatalysis showing intense solubilization of suspended organic matter, such as pathogen cell walls and humic compounds by ozonolysis and UV photolysis, respectively (Ariunbaatar et al., 2014; Gomes et al., 2013). Adsorption of organic matter on titanium surfaces during the reaction process reduced its ability to degrade the suspended organics, hence low DOC levels (Gusain et al., 2020).

BOD levels were reduced to 2 mg/l and 5 mg/l from 18 mg/l after 60 minutes of ozonolysis and TiO_2 photocatalysis, as observed in figure xx, as a result of mineralization of organic matter during ozone and TiO_2 photocatalysis (Al-Mamun et al., 2019). The slight reduction in the BOD level, from 18 mg/l to 12 mg/l, is associated with suspended organics blocking the UV rays from reaching the targeted organics (Sheng et al., 2013).

Humic concentration decreased significantly from 0.337 to; 0.171 and 0.256 during ozonolysis and TiO_2 photocatalysis, respectively, while increasing from 0.337 to 0.399 after 60 minutes of UV photolysis. The breakdown of the humic compounds by ozone into simpler byproducts like organic acids reduced humic levels (Zhong et al., 2018). Photo fragmentation of humic compounds by UV may have increased the functional groups of humic compounds, increasing humic values (George et al., 2014). Competition of inorganic compounds for the reactive oxygen species resulted in slight degradation of the humic compounds during TiO_2 photocatalysis (Gusain et al., 2020).

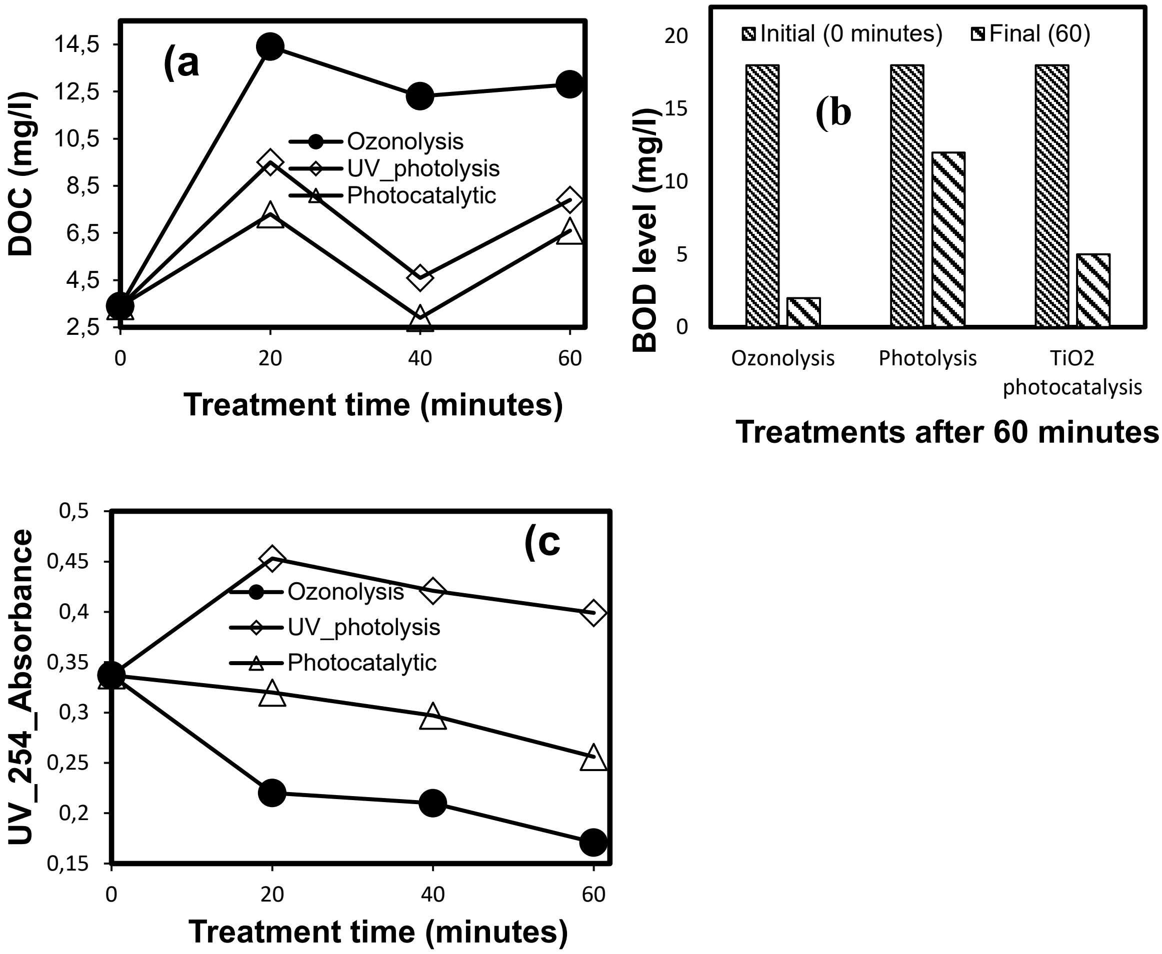

Figure 4.3. Reduction in DOC (a), BOD (b), and humic (c) during the AOPs degradation of pollutants in the primary effluent.

4.3.3.2 Change in Turbidity and pH

Low turbidity shows the reduced levels of the suspended organic materials in the effluent. Reduction of turbidity from 14 NTU to 2 NTU indicates an effective removal of suspended particles from the effluent by ozonolysis (Otieno et al., 2019). UV photolysis can only reduce a small percentage of turbidity due to the deflection of the UV rays by the suspended organic materials in the effluent (Ali et al., 2022). Oxidation of the suspended particles and the adsorption of the dissolved organic matter by the catalyst titanium resulted in the reduction of turbidity (Boroski et al., 2009; Gusain et al., 2020).

When proteins released from the dead pathogen cells are broken down, basic amine oxides or other alkaline nitrogen-containing compounds are produced, which, when further broken down, increases the effluent's pH (Ma et al., 2012; Schumperli et al., 2012).

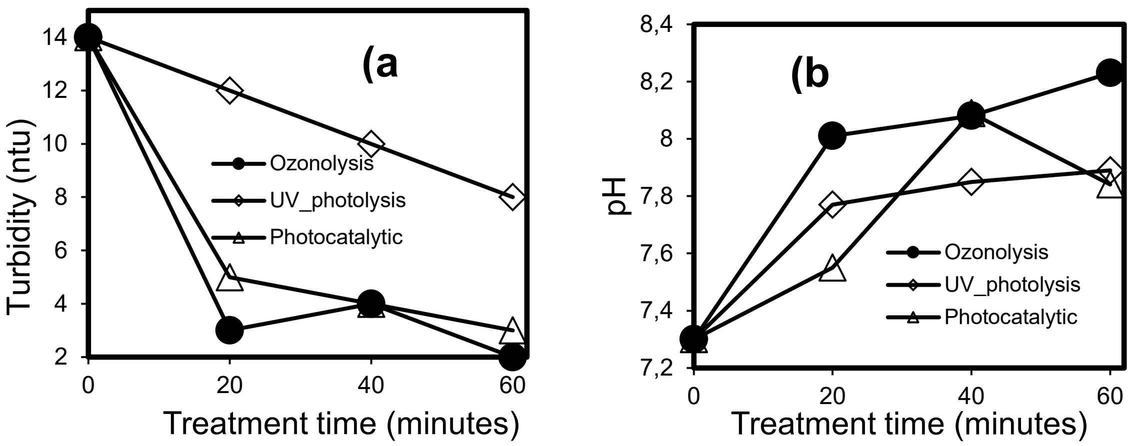

Figure 4.4. Reduction in Turbidity (a) and pH (b) during the AOPs degradation of pollutants in the primary effluent

4.3.3.3 Elimination of pathogens

The ozonolysis and TiO_2 photocatalysis of the primary DEWATS effluents led to the complete elimination of *E. coli* Figure 4.5(a) and Total coliforms Figure 4.5(b). These two processes are thus more effective for eliminating bacteria than COD and other organic compounds. However, UV photolysis did not completely reduce pathogens, which is associated with the abundance of the suspended particles that would have absorbed or scattered the UV rays from reaching the targeted pathogenic cells (Yasar and Tabinda, 2010). Some pathogens would also produce biofilms, protecting them from UV rays (Raza et al., 2021).

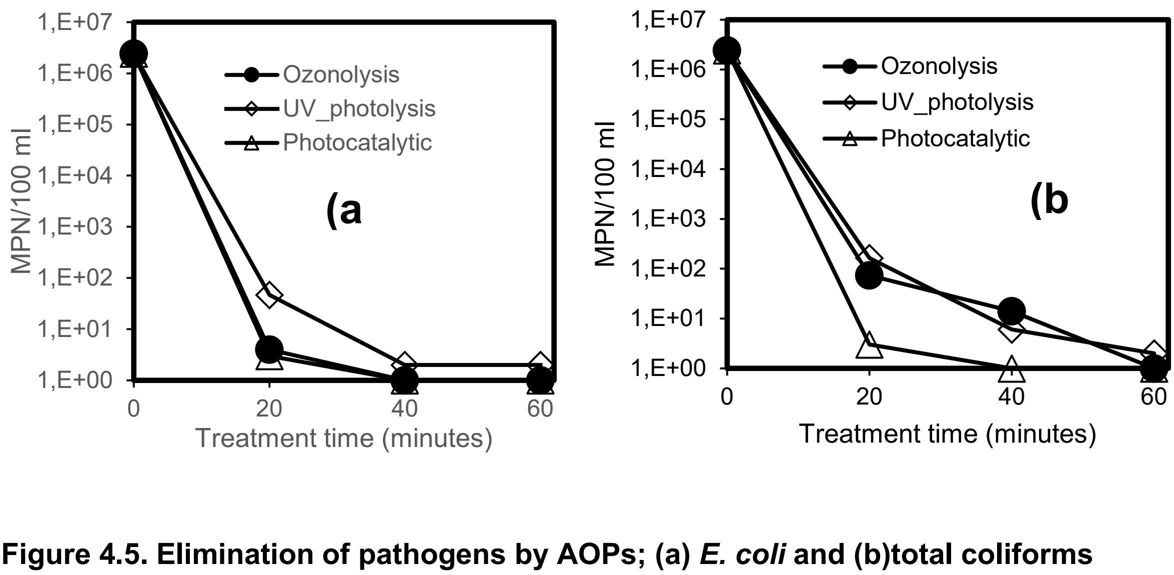

Figure 4.5. Elimination of pathogens by AOPs; (a) *E. coli* and (b)total coliforms

4.3.3.4 Pathogen regrowth following 4 days storage of the AOPs treated effluent.

After a complete disinfection of the effluents, the treated samples were kept at room temperature for 4 days in the dark. This was done to mimic the standard water storage tanks. The ability of pathogens to regrow validates the effectiveness of the treatment method. The highest *E. coli* and Total coliform log regrowth on samples treated for 60 minutes were observed on TiO_2 photocatalysis (2.5-log and 2.7-log, respectively), followed by UV photolysis (0.5-log and 2.2-log). On the contrary, ozonolysis did not record any pathogen regrowth after 4 days. Ozone causes cross-linking within the pathogen's nucleic acids (DNA and RNA) and impairs bacteria's capacity to regrow their genetic material (Magdeburg et al., 2014).

Ultraviolet (UV) radiation causes pyrimidine dimers to form between pathogen cells' DNA or RNA molecules. If left unrepaired, these dimers lead to mutations or cell death (Delorme et al., 2020). In this study, the regrowth levels in the UV photolysis samples show that pathogens counteracted the formation of these dimers, which ceased the mutation process or cell death (Barlev and Sen, 2018; Cordero and Casadevall, 2020; Pavan et al., 2020; Raza et al., 2021).

The exponential regrowth of pathogens in the TiO_2 photocatalysis samples is associated with studies showing TiO_2 photocatalysis being very slow and taking longer to completely oxidize pathogenic cells (Joost et al., 2015; Kim et al., 2013). This suggests that under-oxidized pathogen cells were produced after 60 minutes of treatment. Also, the desorption of the organic materials that were tapped on the titanium surface during the storage period provided food for the pathogens, hence the exponential regrowth (Kim et al., 2013).

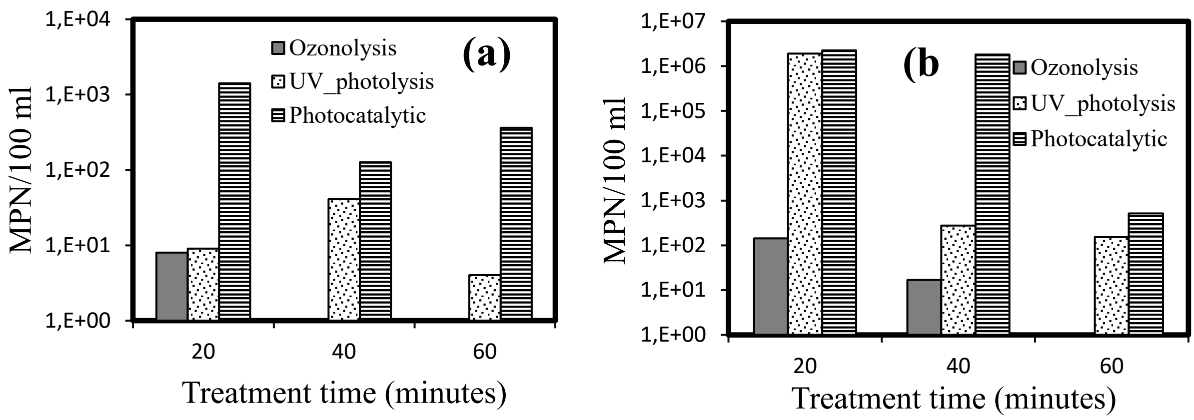

Figure 4.6. Pathogen regrowth following 4 days storage of the AOPs treated effluents; (a) *E. coli* and (b) total coliforms.

4.3.4 Conclusions

This study investigated ozonolysis, UV photolysis, and TiO_2 photocatalysis as treatment methods to polish up DEWATS effluent for compliance with discharge standards and agricultural reuse. TiO_2 photocatalysis significantly reduced BOD, soluble COD, humic levels, and pathogens while increasing the pH and DOC. Also, significant pathogen regrowth was seen after four days of storage, suggesting potential challenges in maintaining microbial control under TiO_2 photocatalysis. Ozonolysis treatment significantly reduced BOD, soluble COD, humic, and turbidity and eliminated the pathogens while increasing the pH and DOC.

Notably, the absence of pathogen regrowth after four days of storage demonstrated the ability of ozonolysis to sustain improved microbial control. UV photolysis resulted in marginal reductions in BOD, turbidity, and pathogens, with increased pH, DOC, and humic levels. After four days of storage after photolysis treatment, a slight pathogen regrowth was seen. In comparison, ozonolysis proved to be the best AOP that would fully treat the AF effluent to meet the required wastewater standards for agricultural use. However, extensive studies on these processes should be carried out to determine the following;

- Effect of process parameters such as pH, time, and initial concentration on these AOPs.
- Cost and kinetics analysis of these AOPs.

5 BIORESOURCES RECOVERY: URINE BASED PRODUCTS RECOVERY AND CO-COMPOST FORTIFICATION

5.1 Introduction

One of the considerations in transitioning to a circular bioeconomy is having the appropriate technologies to contain, process and treat the respective waste stream. Majority of nutrients found in human excreta come from urine. About 88% of N and 66% P found in wastewater emanate from urine (WWAP, 2017). Disposal of human excreta into water bodies cause pollution and death of aquatic life. This has implications on tourism and livelihoods for those depending on fisheries for a living. Furthermore, most countries in Sub Saharan Africa are struggling with food insecurity, degraded soils and nutrient mining. Which are exacerbated by minimal use of organic fertilisers. Addressing environmental pollution and food security through nutrient recovery from human excreta streams is of utmost importance.

Farmers expect fertilisers to perform better than their current practices. In promoting the transition towards a CBE, the respective fertilisers should be able to improve their crop yields. Organic fertilisers such as co-compost only provide organic C which make them good soil conditioners. Currently the use of co-compost is minimal due to myriad factors. A report by IWMI (2016) showed that although there are benefits associated with co-compost production, its uptake is not automatic and several issues have to be addressed, ranging from market dynamics, education and awareness and even value addition by adding extra nutrients such as NPK. Otoo et al. (2018) conducted a comprehensive market analysis of a fortifier, a commercial co-compost with extra NPK. Authors concluded that there is strong potential for commercialising the fortifier fertiliser if farmers are given adequate awareness. Therefore, fortification of organic fertilisers such as co-compost with other NPK fertilisers is one of the value addition strategies for use as an agricultural input. The production of co-compost after mixing urine products such as struvite, crop residues and cow dung produces high quality products with high concentrations of nutrients (Karak et al., 2015). Fortification of co-compost for example with other NPK rich excreta materials is an example of upcycling materials which adds to resulting product. Salvador et al. (2021) did a comprehensive review on key aspect of designing and managing a business model in a circular bioeconomy. The authors mentioned a variety of aspects ranging from logistical, customer satisfaction, feedstock availability, establishing resilient value chains and most importantly value creation of the product to cover costs. Value creation of co-compost through fortification has a positive impact on covering production costs while increasing its economic viability.

As mentioned in Section 2.5.5 economic viability refers to financial, social and environmental gains of a respective practice. In this juncture, valorisation of urine and its fortification with co-

compost protect the environment from pollution, minimise burden of diseases to the public and improve livelihoods through income generation channels.

The fortification should generate products which a legally compliant with national regulations. In South Africa, the underlying regulation is the Fertilisers, Farm Feeds, Agricultural remedies and Stock remedies Act no 36 of 1947 (DALRRD, 2017), which regulates registration of fertilisers in accordance with public health and consumer protection regulations, which could not be detailed now. In this regard, registration of the respective product increase consumer acceptance and trust as well as potential fast adoption by farmers. Gwara et al. (2023) conducted a study which clearly showed high willingness to use excreta derived fertilisers provided that they are certified by trusted regulatory authorities.

In cognisance of the importance of co-compost as a soil conditioner and the potential of urine to provide plant grown nutrients, this section reports on the potential benefits of fortification of HEDFs. The study assessed and validated the recovery of nutrients from urine through struvite production and fortification of sewage sludge-based co-compost. The study further assessed the legal compliance of the fortified product with the South African Fertilisers, Farm Feeds, Agricultural remedies and Stock remedies Act, 1947 (Act no 36 of 1947). The respective issues of consideration with regards to potential involvement of community members in fertiliser production, constraints for viable business models and institutional recommendation to spearhead the practice were discussed.

5.2 Materials and methods

5.2.1 Stakeholder engagement and feedstock collection

The precipitation and characterisation of struvite was done at the Controlled Environment Research Unit (CERU) University of KwaZulu-Natal Pietermaritzburg campus. Dried urine was obtained courtesy of the Swedish University of Agricultural Sciences, Department of Energy and Technology, Sweden (SLU Umea).

Two types of co-composts used in this study were produced from experimental windrows in one of the private companies working within the RUNRES innovation platform. The co-compost was made from 15% and 25% sewage sludge mixed with 85% and 75% green garden waste respectively see PPL4 in Figure 4.1. The composting process was done for over four months and allowed to stabilise prior to sampling.

In addition, this study was planned to link with the RUNRES innovation on school DEWATS, which involve urine separation and blackwater treatment as per the PSS2 module see Figure 4.1. The school DEWATS project delayed and through consultation with stakeholders from eThekwini municipality alternative sites were identified. Urine was collected from the urine diversion research pilot urinary outside the toilets at the Durban Fresh Market (Figure 5.1). The urinals were provided for public use by the Warwick Zero Waste project partnering Durban University of Technology (DUT), Durban Future Centre, Asiye eTafuleni and Groundwork. The urinary was built after the toilets provided by the municipality had become malfunctioning due to blockage and failure of a proper maintenance. The urine is collected daily into 25 L plastic containers and disposed down the drainage system. A volume of approximately 500 L of urine is collected and disposed daily. The collected urine from the urinary collection containers to 25 L containers for transportation to Pietermaritzburg as shown in Figure 5.1.

Figure 5.1. Urinals at the urine diversion research pilot urinary outside the toilets at the Durban Taxi Rank in Durban (top) and collected urine in 25 L containers (bottom).

5.2.2 Laboratory studies for struvite precipitation

A study was done as a single factor analysis with 100% urine and 50% urine + 50% water as treatments to assess the struvite yield at different concentrations. The experiment was replicated three times resulting in six experimental units. Each experimental unit was represented by a 2 L bucket with a lid. A volume of 1000 mL was used for the experiment. The urine pH was monitored for 7 days. This stabilises the urine after addition of magnesium allowing struvite precipitation. A stock solution of magnesium sulphate heptahydrate standard was prepared according to methods by Rhoton et al. (2014) and added to the stored urine. A 1.2 M excess $MgSO_4.7H_2O$ was added to 1000 L of urine. The containers were closed and vigorously swirled to allow mixing of urine with the $MgSO_4.7H_2O$. The precipitate was allowed to settle and collected at the bottom of the containers. The struvite effluent was gently decanted, and the remaining precipitate transferred to petri dishes for drying in the greenhouse (Figure 5.2).

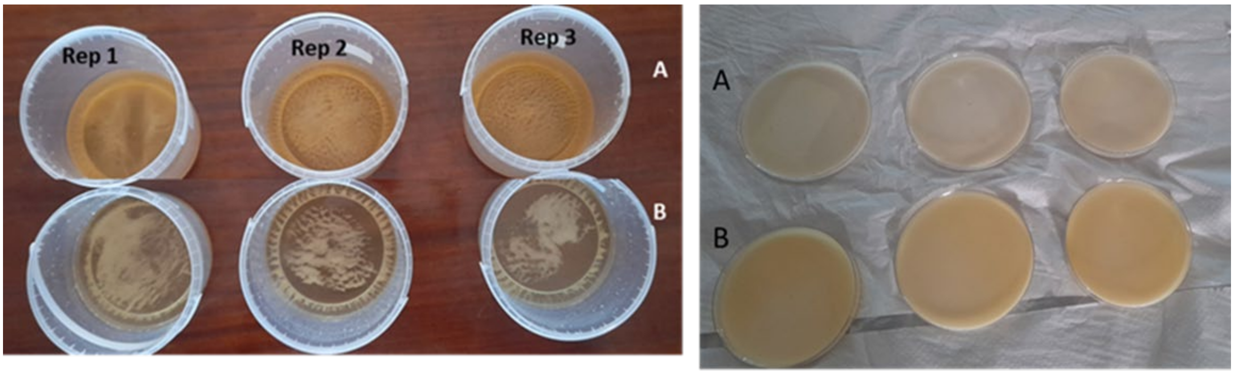

Figure 5.2. Struvite precipitation in 1 L urine (A) 100% urine and (B) 50% urine and the drained struvite for drying.

The struvite effluent was decanted into an empty container and the struvite that settled at the bottom was air-dried in a greenhouse. The solid crust was ground into a powder struvite. The struvite was characterised for yield. The urine, struvite and struvite effluents were characterised for pH, basic cations, heavy metals, ammonium, nitrates, total P, orthophosphates, total N according to standard methods (APHA et al., 2017). The ground powder crystals were analysed using XRD to confirm the presence of struvite. The surface structure of the struvite was viewed using the scanning electron microscope.

5.2.3 Lab scale co-compost fortification

The co-compost and urine derived fertiliser were mixed to make an organic fertiliser named "organic fertiliser mixture" (DALRRD, 2017). According to the South African Fertiliser Farm Feeds and Remedies Act of 1947 an organic fertiliser mixture is defined as a mixture of registered organic fertilisers, which in this context refer to urine derived fertilisers and co-compost as presumed registered organic fertilisers.

The co-composts were weighed and mixed with the nutrient sources such as struvite and dried urine. The two composts 15% and 25% sludge were mixed with the struvite at the following ratios, 1:5; 1:10 and 1:20 (nutrient source: compost) as shown in Table 5.1. The co-compost/dried urine, co-compost/struvite mixes and struvite were analysed for physical and chemical properties. The CNS analysis and moisture were also carried out on the co-

composts. The ICP-AES was used to analyse for heavy metals according to standard methods at chemistry department of the University of KwaZulu-Natal.

Table 5.1. Quantities of struvite and dried urine mixed with co-compost to make compost fertiliser.

		Nutrient source	
Compost faecal sludge percentage (%)	Compost (g)	Struvite (g)	Dried Urine (g)
25	50	10	-
25	50	5	-
25	50	2.5	-
25	50	-	10
25	50	-	5
25	50	-	2.5
15	50	10	-
15	50	5	-
15	37.5	2.5	-
15	37.5	-	10
15	25	-	5
15	37.5	-	2.5

5.2.4 Data analyses and reporting

Analysis to assess the difference between mixing ratio treatments was done using the GenStat 21^{th} edition. General Analysis of Variance (ANOVA) was done and means were separated at 5% level of significance using the Bonferroni multiple comparisons with letters. The mean values for respective parameters were compared with the South African Fertiliser Farm Feeds and Remedies Act of 1947 to assess compliance with registration as a mixed organic fertiliser.

5.3 Results and Discussion

5.3.1 Struvite precipitation

The changes in pH during struvite precipitation was monitored (Figure 5.3). The initial pH of diluted and undiluted urine was 6.93 and 6.88 respectively and increased in both diluted (50% urine) and undiluted (100% urine) stored urine. The 50% urine pH increased faster than 100% urine until 72 hours when both treatments reached a pH of 9.24. After this time pH in 50% urine increased to 9.42 compared to 9.29 for 100% urine. Naturally, when urine is excreted, it exposed to hydrolysis due to the presence of the urease enzyme which is ubiquitous in nature. The urea in urine is broken down to ammonia resulting as the pH increases. This effect was more pronounced when urine was diluted. These results corroborate findings by Liu et al. (2014) who observed pH increase from 6.8 to 9.0 in all urine solutions diluted at 100, 50 and 25% urine diluted with water within 5 days and attributed it to hydrolysis via urease action.

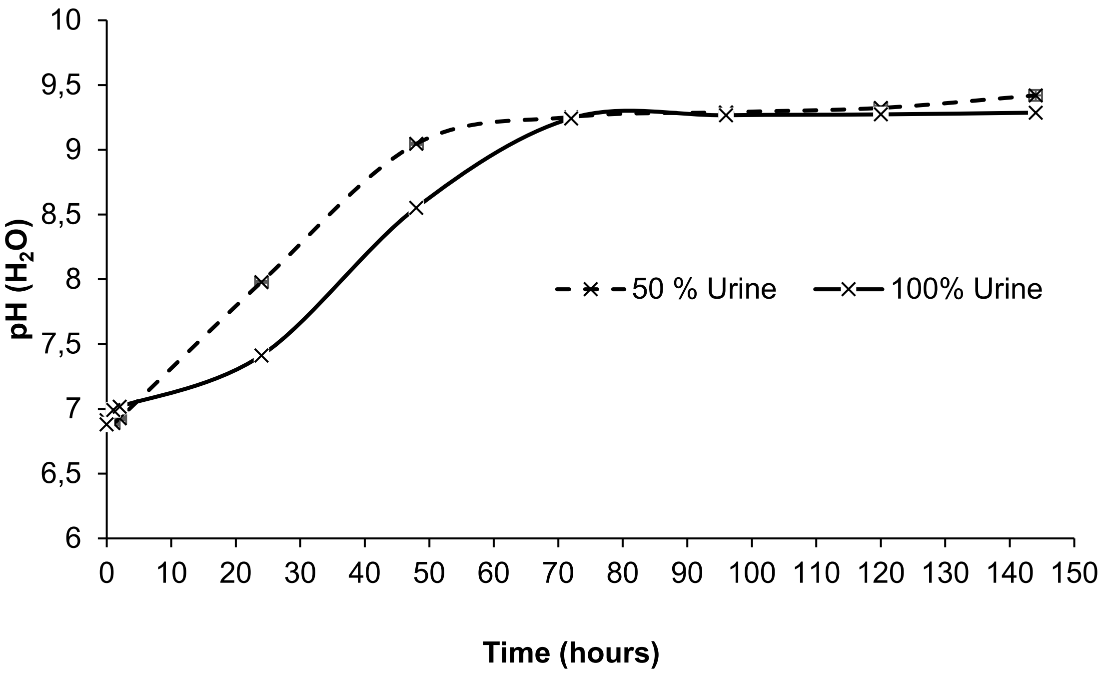

Figure 5.3. pH of urine during storage at 50% urine dilution and 100% urine (no dilution).

Struvite precipitated from 50% urine was lighter in colour compared to that precipitated using 100% urine (Figure 5.4). This could be attributed to the change in colour that occurs when water is added. Dilute urine has a lighter colour than undiluted urine hence the differences in the colour of the respective struvite formed. The struvite crystals were smaller in 100% urine compared to 50% urine (Figure 5.4). These findings corroborates with findings by Liu et al. (2014) who reported smaller struvite particles sizes at lower dilutions (100% and 50% urine) compared with higher dilutions (25% urine). Smaller struvite particles obtained using 100% urine are more likely to be washed away with the effluent upon filtering. On the other hand, larger crystals obtained at lower concentration (50%) facilitate the recovery, transport, and commercial operations of the final product. However, from a sanitation and nutrient recovery point of view, the use of 100% urine is more sustainable to recycle larger amounts of urine.

Figure 5.4. Precipitated struvite (top) 50% urine (A) and 100% urine (B) and SEM images of struvite precipitated using 50% diluted urine (bottom).

The struvite yield in samples precipitated using different urine concentrations showed a significant difference (Figure 5.5). Dilution increases the magnesium concentration from water resulting in spontaneous precipitation of P into other compounds. This was confirmed by the lower percentage of struvite shown on the XRD patterns in diluted urine (93.8%) compared to undiluted urine (97.2%) (Figure 5.5). In such cases, the Mg: P molar ratio increases. The decrease in the concentration of PO_4^{3-} result in lower reaction with $MgSO_4.7H_2O$.

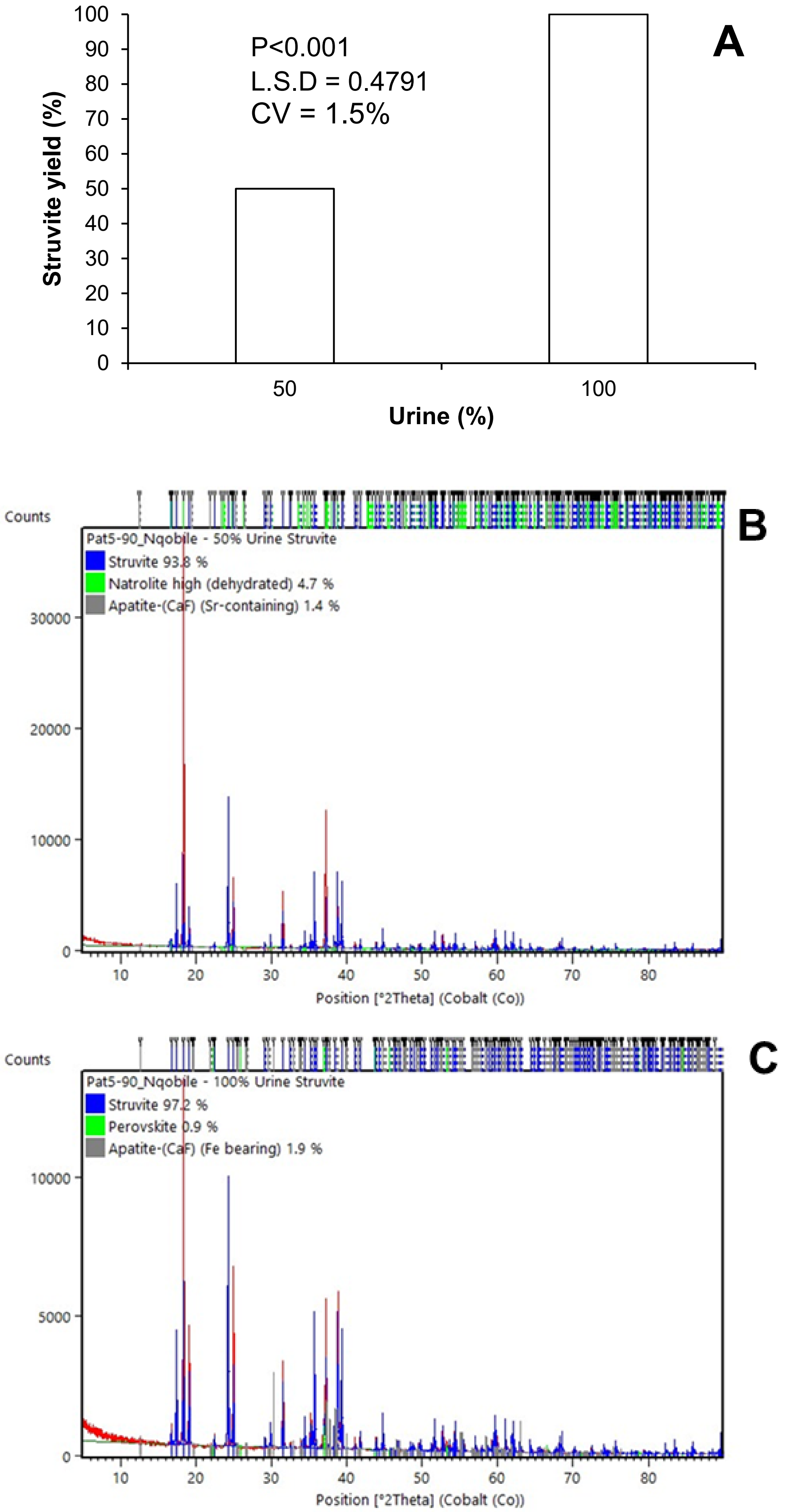

Figure 5.5. Struvite yield of urine diluted with 50% tap water and non-diluted urine (A) and XRD patterns of struvite for 50% tap water diluted urine (B) and 100% urine (C) and other minerals that precipitated along with struvite .

5.3.2 Co-compost fortification

Dried urine (DU) had the highest pH at all mixing ratios ranging from 12.7 to 13.2 (Figure 5.6). The high alkalinity of the DU co-compost is attributed to the inherent pH of the DU (average pH of 13). All struvite co-composts had lower pH ranging from 7.9 to 8, which was caused by the lower struvite pH (8.5) than that of DU before addition. Higher pH of organic fertilisers allows them to be used as lime in acidic soils. This is important in Sub Saharan region where 30% of the soils are acidic.

The challenge comes with fertiliser certification. The South African and even Indonesian regulations require a registered organic fertiliser to exhibit a pH between 4 – 9 with the target value of 6.8 – 7.5 (DALRRD, 2017; Devianti et al., 2021). Meaning that struvite co-compost complies with the regulations in this regard. The DU co-compost needs further pH correction interventions such as blending with sulphate containing amendments. Compound such as iron sulphate have been proved to lower the pH of an organic fertilizer as reported by Paradelo et al. (2015).

On an agricultural point of view, raising pH of an organic amendment up to 12 for 2 hours or 11.5 for 22 hours aid vector reduction (Snyman et al., 2006). This makes the DU co-compost attractive to consumers. Wilde et al. (2019) found out that people are sceptical to handle the urine when not treated. After educating a group of farmers about the processed nitrified urine, which is odourless, people showed interest in the product. This indicates that the pH in DU co-compost can be an advantage during product stabilisation.

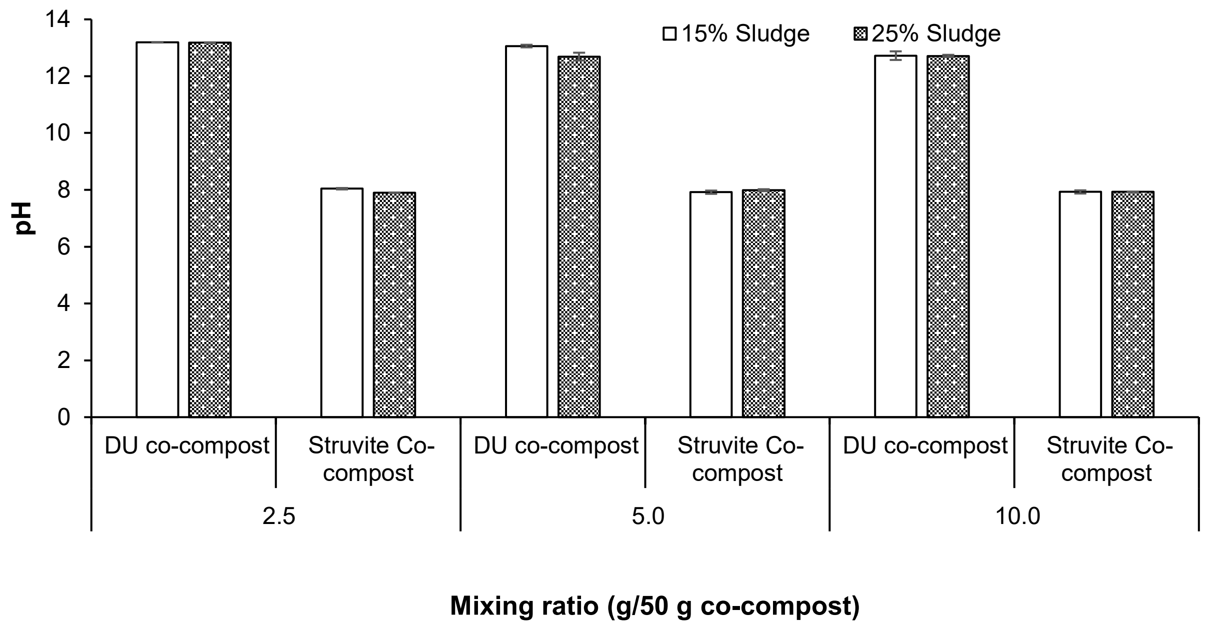

Figure 5.6. pH (KCl) of dried urine and struvite co-compost.

Nitrogen is the most important mineral nutrient in agriculture which is benchmarked as the reference for crop fertiliser requirements (Tesfamariam et al., 2020). Although the total N was increased in both co-composts using the different nutrient sources (DU and struvite). The nutrient content of the compost fertiliser mix made using DU had the highest total N at the highest mixing ratio of 10 g struvite per 50 g co-compost (Figure 5.7). This was followed by struvite co-compost at the same mixing ratio (1.9%). This makes the DU co-compost a better organic fertiliser than struvite co-compost in terms of N content. Dried urine technology was developed to capture the N that is lost during struvite precipitation. The introduction of a MgO or $Mg(OH)_2$ source allows simultaneous precipitation of struvite with retainment of nitrogen. According to Simha, Prithvi et al. (2021), alkaline media raises the pH above 11, inhibiting hydrolysis of urea. After drying at elevated temperatures between 50 and 60 °C, urine is concentrated up to 48 times, yielding a high-end value product with the following fertiliser value: 10% N, 1% P, and 4% K. At the mixing ratio of 10 g per 50 g co-compost sample, almost half of the total N could be used to enhance the co-compost fertiliser. Higher doses of DU are thus important for a high value co-compost product per unit mass, which is economical to the farmer in the sense of transporting more nutrients than the bulk product.

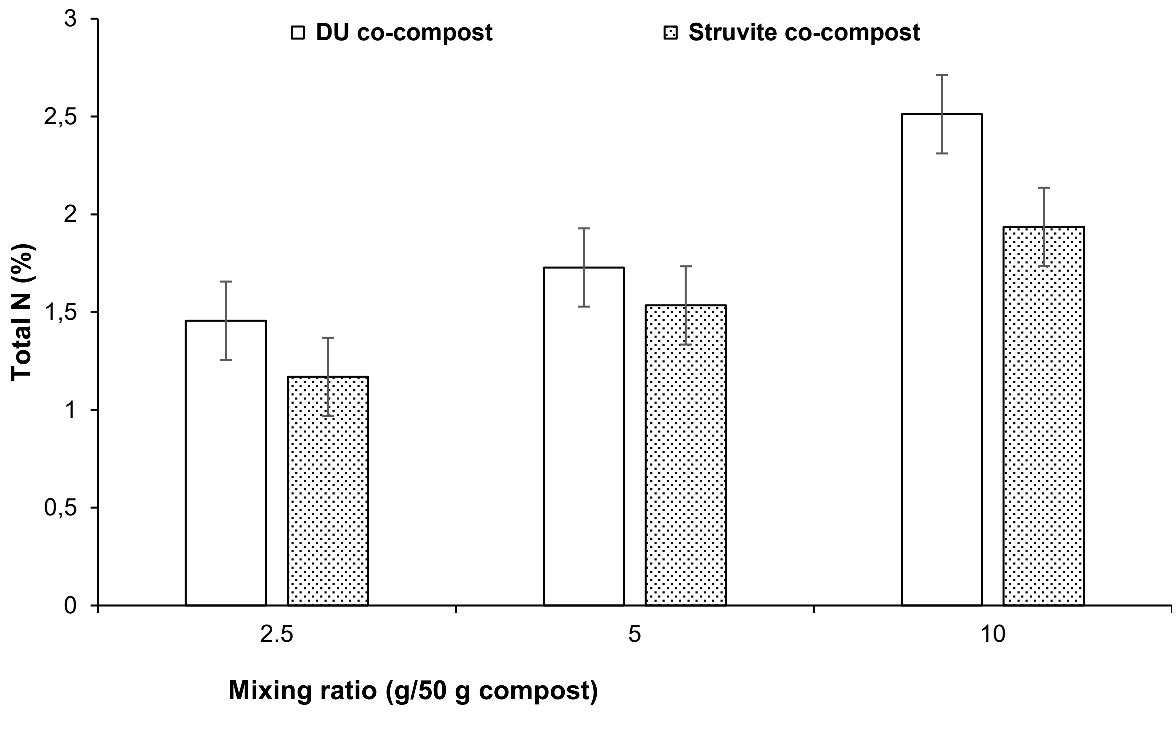

Figure 5.7. Total nitrogen in co-compost samples treated with dried urine and struvite and different application rates.

Struvite had the highest total P at both compost mixing ratios (Figure 5.8). The highest total P (46.8 g/kg) was observed in 25% sludge compost at highest mixing ratio using struvite. In an experiment carried out on co-composting agricultural waste using struvite, the resulting co-

compost made had the following NPK nutritional value: 21.59, 3.98 and 34.6 g kg^{-1}. In this experiment higher total P in co-compost was attributed to feedstocks where struvite was added before composting (Karak et al., 2015). Struvite-based co-compost makes it an important P fertiliser made from renewable material that can spearhead global call of transitioning from non-renewable agricultural resources such as rock-based P. On a legal point of view the South African legislation has not limitations on the concentrations of total P for registering the organic fertilizer mixture product but this should be declared (DALRRD, 2017).

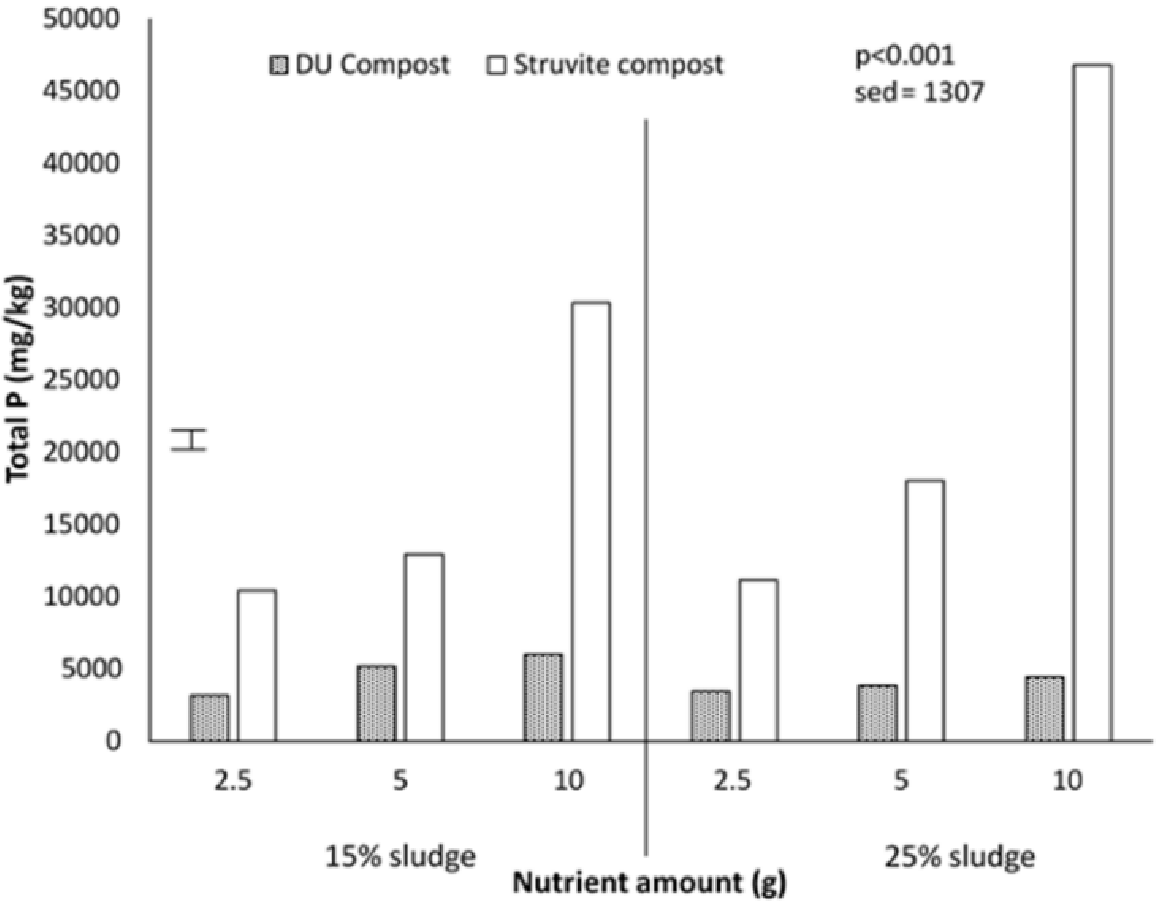

Figure 5.8. Total P in co-compost samples treated with dried urine and struvite at different application rates.

All fertilisers except co-compost amended with struvite at the lowest mixing ratio had total NPK values greater than 40 g/kg (Table 5.2). According to the Fertilisers, Farm feeds, Agricultural Remedies and Stock Remedies, Act No. 36 of 1947, organic fertiliser mixes should have a minimum total N, P and K value of 40 g/kg (DALRRD, 2017). Thus, DU and struvite improved co-compost to an organic fertiliser mixture class except for the DU to co-compost ratio of 5 g/50 g.

Table 5.2. Mean values for total NPK of the composts enriched with DU or struvite.

		Total NPK (g/kg)		
		20	10	5
	15	163.26	45.63	28.75
DU	25	151.2	131.1	107.03
	15	63.32	40.09	40.75
Struvite	25	81.38	47.58	36.63

Mixing the co-compost with DU increased basic cations Ca and Mg compared to co-compost mixed with struvite (Table 5.3). All the Mg and Ca in DU was incorporated into the DU product. Some Ca and K in struvite precipitated into other compounds and could not be extracted for analysis. However, the two mixes did not significantly differ in Mg concentration. The presence of Ca, Mg, K and Na in a DU co-compost provide extra advantages of counteracting the effects of salinity and sodicity.

Table 5.3. Basic cations for co-compost enhanced with struvite and dried urine (DU) at different application rates.

			Basic cations (g/kg)			
Nutrient source	**Faecal sludge co-compost (%)**	**Mixing ratio (%)**	**Ca**	**K**	**Mg**	**Na**
		20	72.7[a]	131.41[f]	3.62[a]	19.87[a]
		10	6.9[a]	19.79[b]	3.36[a]	17.36[a]
	15%	5	4.1[a]	10.35[a]	3.38[a]	15.46[a]
		20	3922.6[c]	89.66[c]	3.58[a]	20.21[a]
		10	2181.4[b]	113.32[d]	3.56[a]	17.61[a]
DU	25%	5	424.3[a]	122.32[e]	3.41[a]	13.80[a]
		20	7.6[a]	13.02[ab]	72.94[g]	9.57[a]
		10	7.7[a]	11.34[ab]	46.99[e]	9.33[a]
	15%	5	6.6[a]	11.61[ab]	21.54[c]	8.93[a]
		20	8.6[a]	15.79[ab]	64.94[f]	11.15[a]
		10	8.2[a]	14.63[ab]	30.64[d]	8.99[a]
Struvite	25%	5	7.9[a]	13.94[ab]	19.13[b]	8.63[a]
p.value			**<0.001**	**<0.001**	**<0.001**	**0.963**
l.s.d			**675.7**	**8.566**	**1.215**	**6.232**
cv (%)			**71.9**	**10.7**	**3.1**	**27.4**

Superscripts a, b, c and d denote means that are significantly different in each column

The pollutant classes for co-compost enhanced with struvite and DU is shown in Table 5.4. The co-compost made using 25% sludge showed higher concentrations of heavy metals when combined with either struvite or DU. The higher the proportion of sewage sludge in a co-

compost is directly linked to the heavy metal content. The sewage sludge emanates from the centralised wastewater treatment system where domestic wastewater mix up with stormwater and other accidental wastewater from industries, elevating heavy metals. After the wastewater treatment processes the heavy metals are adsorbed in the final sludge.

The highest mixing ratio of struvite or DU yielded the highest heavy metal concentration. It is well documented that urine does not contain heavy metals since they are not consumed by human beings and cadmium is even toxic to the human organs (Etter et al., 2015). Indicating that heavy metals could have come from external cross contamination sources. Although the heavy metals have been detected in the DU and struvite co-compost, their potential environmental effects and toxicity in the food chain is negligible. All of them were far below the minimum thresholds of a pollutant class a biosolids according to the sewage sludge guideline (Snyman et al., 2006) as well as the South African Farm Feeds and Remedies Act of 1947 (DALRRD, 2017). Thus, the mixed organic fertiliser can be registered as a commercial fertiliser. Furthermore, the absence of pathogens such as faecal coliforms and helminths eggs are important. Studies proved that co-compost produced with proper moisture correction and turning, maintaining temperatures above 55^{o}C for 7 to 10 days achieve total pathogen elimination (Cofie et al., 2016). On a stability point of view the South African sewage sludge guideline requires at least exposure of the co-compost to temperatures above 40^{o}C for 14 days under aerobic conditions. Even adding the alkaline material to raise the pH can lead to stabilised material unattractive to vectors, thus meeting a stability class 1 material (Snyman et al., 2006). In this regard the high pH of DU and struvite co-compost (Figure 5.6) is evidence enough of stability and pathogen elimination in the product. Even the conditions in which the co-composting was made, high temperatures above 50^{o}C were maintained for more than 14 days and managed to reduce the pathogens levels to standards recommended by the WHO and South African Fertiliser regulation (RUNRES, 2023).

Table 5.4. Heavy metals for co-compost enhanced with struvite and dried urine (DU) at different application rates.

Nutrient source	Faecal sludge co-compost (%)	Application rate (%)	Heavy metals (g/kg) Al	As	Ba	Co	Cr	Ni	Pb	Cu	Fe	Mn	Mo	Zn
DU	15%	20	10.11^{a}	0.14^{a}	0.20^{a}	0.05^{a}	0.21^{c}	0.04^{a}	0.21^{b}	0.18^{d}	49.57^{e}	0.97^{e}	0.05^{a}	0.26^{c}
		10	12.76^{b}	0.13^{a}	0.23^{b}	0.06^{e}	0.34^{h}	0.04^{c}	0.27^{d}	0.16^{c}	52.30^{f}	0.76^{c}	0.06^{a}	0.23^{b}
		5	15.22^{cd}	0.13^{a}	0.25^{c}	0.05^{c}	0.26^{e}	0.05^{d}	0.24^{c}	0.13a	39.81^{c}	0.52^{a}	0.05^{a}	0.20^{a}
	25%	20	12.45^{b}	0.13^{a}	0.20^{a}	0.05^{ab}	0.13^{a}	0.04^{a}	0.19^{a}	0.20^{e}	46.62^{d}	0.85^{d}	0.05^{a}	0.29^{d}
		10	15.50^{cd}	0.13^{a}	0.24^{bc}	0.05^{b}	0.17^{b}	0.04^{b}	0.21^{b}	0.18^{d}	36.90^{b}	0.67^{b}	0.05^{a}	0.26^{c}
		5	16.48^{e}	0.13^{a}	0.27^{d}	0.06^{d}	0.24^{d}	0.05^{ef}	0.24^{c}	0.13^{a}	31.63^{a}	0.69^{b}	0.05^{a}	0.21^{a}
Struvite	15%	20	12.69^{b}	0.48^{a}	0.28^{d}	0.06^{e}	0.25^{e}	0.04^{b}	0.25^{c}	0.14^{b}	47.17^{d}	0.85^{d}	0.06^{a}	0.31^{e}
		10	15.56^{d}	0.42^{a}	0.30^{e}	0.06^{f}	0.21^{c}	0.04^{fg}	0.26^{d}	0.19^{d}	49.52^{e}	0.83^{d}	0.06^{a}	0.31^{e}
		5	15.01^{cd}	0.34^{a}	0.28^{d}	0.06^{e}	0.18^{b}	0.05^{de}	0.25^{c}	0.18^{d}	40.21^{c}	0.79^{c}	0.06^{a}	0.27^{c}
	25%	20	14.64^{c}	0.49^{a}	0.31^{e}	0.07^{g}	0.27^{f}	0.05^{g}	0.31^{e}	0.19^{d}	59.57^{h}	2.40^{g}	0.07^{a}	0.40^{g}
		10	18.83^{f}	0.42^{a}	0.37^{f}	0.11^{h}	0.23^{d}	0.06^{i}	0.32^{f}	0.21^{e}	59.90^{h}	1.04^{f}	0.07^{a}	0.35^{f}
		5	20.55^{g}	0.35^{a}	0.41^{g}	0.07^{g}	0.28^{g}	0.06^{h}	0.33^{f}	0.22^{f}	57.73^{g}	0.76^{c}	0.07^{a}	0.30^{de}
Regulatory limits (mg/kg)			-	15	-	100	1750	200	400	750	-	-	25	2750
p.value			**<0.001**	**0.677**	**<0.001**	**<0.001**	**<0.001**	**0.002**	**0.004**	**<0.001**	**<0.001**	**<0.001**	**0.061**	**0.003**
l.s.d			**0.89**	**0.01**	**0.03**	**0.002**	**0.01**	**0.002**	**0.01**	**0.007**	**2.2**	**0.04**	**0.002**	**0.02**
cv (%)			**3.5**	**1.9**	**2.7**	**2.2**	**2.6**	**2.3**	**2.6**	**2.5**	**1.801**	**2.5**	**2.1**	**2.5**

5.3.3 *Participation of communities in production and utilization*

The project took a transformative approach to resolve societal challenges such as food insecurity, nutrient mining, youth unemployment and unequitable access of resources by establishing a circular bioeconomy. The production of mixed organic fertilisers has socio-economic implications, and this section discusses several barriers and opportunities available to identified communities, taking different lenses such as economic viability, meeting market demands, technical issues, compliance and other socio-political issues.

Fortification of co-compost with urine derived fertilisers provides an opportunity for youths and women to undertake businesses for livelihoods. There are potential markets with this regard if market research is done. Proper market research and community awareness were some of the factors recommended by Otoo et al. (2018) as crucial for the fortified co-compost success. Studies by Gwara et al. (2023) showed that if the products are certified the farmers are willing to use them and even people along the value chain are willing to consume final food products. The is not a local issue even beyond the European countries, where circular bioeconomy products are deemed to be of high quality (Frijns et al., 2016).

Having available market is not a challenge but the major issue is economic viability. On a financial point of view the major challenge is economies of scale to meet market requirements and marginal returns (Otoo et al., 2016). Furthermore, the co-composting process takes approximately 4-6 months and its of utmost importance to produce enough quantities for significant financial returns. Current evidence shows that co-compost production is not financially profitable. For example, the Sustainable Organic Integrated Livelihoods (SOIL) organisation from Haiti is producing co-compost for ecological restoration rather than income generation (Piceno et al., 2017). The practice is helping various households manage their excreta waste, which is positive impact considering potential challenges caused by poor excreta management. The same interlink with economies of scale, relating to the capacity of identified communities to process adequate quantities for health and environmental impacts.

Another challenge is availability, logistics and quality of feedstock. During the project the identified urine collection hotspot (Durban Market) was far from the processing plant (Pietermaritzburg). This issue has been raised by Etter et al. (2015) after conducting an economic viability study using a business canvas. Secondly outsourcing industrial grade MgO with desired struvite yield was a limitation which prohibited large scale production of struvite during the project period. Entailing that proper procurement research is needed to understand where to outsource the feedstock at sustainable prices.

During participatory workshops the identified communities were generally small-scale farmers which are resource constrained and not able to afford even farming implements. They cannot afford to operate organic fertiliser production at scale. A viable business model will work through public private partnerships. This involves identification of busy areas where the public urinal and a valorisation can be installed. Local municipalities may partner with a private company who can invest machinery and resources to produce co-compost at scale. The same model has been used by the RUNRES innovation (RUNRES, 2023).

5.4 Conclusions and recommendations

Undiluted urine yields more struvite with higher phosphorus content. Diluting urine has effect on struvite crystal size; hence it is important that when struvite machines are made, the filtering cloth should have smaller pores sizes to allow maximum struvite capturing from the struvite effluent. The addition of an external nutrient source to co-compost using human excreta derived sources such as dried urine or struvite has the potential to increase the fertiliser value of sewage sludge/green waste co-compost. The DU increased the pH of a DU + co-compost fertiliser and this can be used in highly acidic soils predominant in the Sub-Saharan Africa. The fortified urine complied with the South African Fertilisers, Farm Feeds, Agricultural remedies and Stock remedies Act no 36 of 1947 for registration as an “organic fertiliser mixture”. Commercial production of the fortified co-compost at viable scale needs strong investment in resources and linkages with feedstock sources.

Recommendations

- Fortification of DU and co-compost produces a highly alkaline fertilisers which should be added sulphate containing compounds to neutralise the pH.
- Proper procurement research is needed to understand where to outsource the feedstock for dried urine or struvite production at sustainable prices.
- The production of fortified co-compost is financially feasible if operated by a private company which afford to invest in equipment for large scale production.

6 SUSTAINABLE PRACTICES: AGRICULTURAL TRIALS

6.1 Introduction

Current food systems in low-income communities of South Africa are not sustainable. Small scale farmers are unable to achieve their best yield potential due to degraded soils and inability to afford agricultural inputs such as fertilisers, high quality planting materials and irrigation. These challenges are exacerbated by nutrient mining and minimal utilisation of organic fertilisers. Recovery of nutrients and materials from organic waste materials and agricultural use is one the well proven approaches to increase soil productivity for optimal yields. Transitioning to a circular bioeconomy should take multifaceted approach, dealing with existing challenges, co-creation of eco innovations in recognition of indigenous knowledge systems, capacity building and establishing of viable business models (Okem and Odindo, 2020; Rizos et al., 2016).

This section focused on best agricultural practices to maximise the use of HEDFs. In this regards the focus was centred towards minimising perceived health risks through implementation of multi barrier approaches of the SSP, sustainable agricultural management practices to minimise environmental pollution, climate change mitigation, protect soil biodiversity and resource efficiency as part of the package (Odindo et al., 2022b).

6.2 Bishopstowe case study

6.2.1 Study site characterisation

6.2.1.1 Background

Prior to agricultural use of any HEDF, the identified site was assessed as recommended by the practical guideline (Odindo et al., 2022b). The guideline encourages land users to assess the site for irrigability and land use potential. This provides a guide on applying the best practices for safe and sustainable agriculture. A landscape scale site survey was done as guided by some indicators of the 13 agroecological principles (Barrios et al., 2020; De Marchi et al., 2022; Meuwissen et al., 2019).

6.2.1.2 Methods

The Bishopstowe Agroecological Living Lab (BALL) located in uMshwati municipality (29°35'09.9"S 30°28'45.4"E) was assessed. The GIS team from the UKZN geography was invited to assess the physical features at the site, where together with the project scientists and farming cooperatives came up with proposed land use plan map. The bioresources information for Bishopstowe was obtained from the Cedara, Department of Agriculture Land Reform and Rural Development (DALRRD) database (Camp, 1999). The characterised site features were agricultural land potential, climate data (temperature, chill units, heat units, rainfall and evaporation), alternate crop suitability by climate and erosion hazard.

Soil physical properties such as textural class was determined by collecting soil samples at 0.3 m intervals down to 1 m. Some other three samples per layer were collected separately, packed and used for particle size analysis (soil texture analysis). The soil samples were submitted to Fertility and Advisory Services (FAS) at Cedara Analytical Services (CAS), DALRRD, KwaZulu-Natal. Soil particle size analysis was done following the hydrometer method (Bouyoucos, 1962). The textural class was determined using the United States Department of Agriculture (USDA) textural triangle (USDA, 2023). The soil textural class was used to estimate soil moisture retention capacity at field capacity (FC) and permanent wilting point (PWP) (Gavrilescu, 2021). The bulk density was estimated using soil textural class based on a Table by MPCA (2023).

Some soil samples were collected from five different spots within the field and bulked to form composite samples in triplicates. The samples were submitted to FAS for the analysis of organic carbon, cation exchange capacity, nutrients (organic N, mineral N, extractable P, organic P, extractable K, Ca, Mg, Cu, Al and Fe), soil salinity, exchangeable Na, pH, acid and base saturation according to the standard methods (Manson et al., 2020). Organic carbon was done following the Walkley-Black chromic acid wet oxidation method (Walkley, 1947). Crop fertiliser requirements for maize, cabbage and chilli were requested.

6.2.1.3 Results and discussion

6.2.1.3.1 Bishopstowe classification

According to the Bioresources Unit (BRU) of South Africa the surveyed site; Bishopstowe Agricultural Living Lab (BALL) located in Bishopstowe, uMshwati municipality (29°35'09.9"S 30°28'45.4"E), belongs to the group Wb12. Whereby W represent rainfall of between 801-850 mm per year. The b represents the altitude of between 451-500 m above sea level and 12 is the occurrence of the Wb code in KwaZulu Natal. This means Bishopstowe is generally under humid conditions as put forward by Ogbazghi et al. (2016). This is important in estimating the mineralisation rate of organic fertilisers (Tesfamariam et al., 2020) such as co-compost. The altitude of 451-500 m above sea level means the site is within the lowland areas of South Africa. According to Goulart et al. (2020) lowland areas are predominantly hydromorphic and poorly-drained soils that can mostly support rice cultivation. The authors even mentioned that dryland crops can be successfully grown there. Halimatunsadiah et al. (2016) enlisted various vegetable crops such as chillies, long bean, *Brassica spp.* and cucumber in that chronological order as some of the vegetable crops grown in lowland areas.

6.2.1.3.2 Climate

The climatic data for BALL is reported in Table 6.1. The rainfall season generally stretch from September to March and the winters a relatively drier. The annual E_{pan} evapotranspiration is 1 690 mm while the rainfall is 832 mm, meaning irrigation is required especially in winter (April to August). The heat units at base temperature of 10°C, for example from October and March, are about 1 855 and crops such as maize grow well in that area since it needs heat units of between 1 500 and 1 800. The other important aspect about the site is that frost is occasional (result not shown), hence frost sensitive tropical and sub-tropical crops may be grown all year round.

Table 6.1. The climatic data for BALL obtained from the BRU database.

Variable	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Median Rainfall (mm)	132	106	96	45	16	4	6	17	43	75	98	113
Mean Rainfall (mm)	144	119	91	58	32	12	15	26	54	77	95	109
Epan (mm)	177	154	148	124	106	95	105	130	148	159	160	184
Max Temp (°C)	23.9	26.7	26.1	24.4	22.4	20.3	20.4	21.8	23.2	23.8	24.5	26.4
Min Temp (°C)	16.2	16.3	15.2	12.3	9.1	6.2	6.1	8.1	10.5	12.0	13.6	15.2
Heat units (base 10°C)	353	324	329	250	179	96	100	153	205	245	270	334
Heat units (base 4.4°C)	527	482	503	418	352	264	274	327	373	418	438	508
Heat units (base 5°C)	508	465	484	400	334	246	255	308	355	400	420	489

*Epan is the evapotranspiration measured from a reference point using the evaporation pan, Temp is the temperature, Min=Minimum, Max=Maximum.

6.2.1.3.3 Dominant ecotype

The most dominant ecotype in the area is B.1.1.s which occupies approximately 32.68% of the total BRU in that area (Table 6.2). Most of the soils are well to moderately drained. Some studies investigated the effects of poorly drained soils on erosion (Sharpley et al., 2001) and microbial activities controlling nutrient dynamics (Van der Laan, 2010). Based on the aforementioned characteristics the BALL is classified as an arable ecotype, which according to Camp (1999) consists of a soil with <15% clay content, soil type A-D, rooting depth of >500 mm and slope of ≤12%. In this case the slope is within the range of 12-40% meaning that some soil erosion management such as contour planting might be needed. However, the

Fb rating of 5-6 is considered as moderate erosion risk, although the BRU encourage the Fb value to be adjusted for local area, the erosion related environmental pollution is less likely to be encountered.

Table 6.2. Classification of the BALL land based on dominant ecotypes.

Ecotype	Area (ha)	% of BRU	Clay content (%)	Depth Range (mm)	Slope range	Fb Rating	Terrain units
B.1.1	689.8	9.67	35-55	800-1 200	1-12	6.0	1,3,5
B.1.1.s	2 264.8	32.68	35-55	800-1 200	12-40	5.4	3,5
B.1.2.s	682.3	9.86	15-35	800-1 200	12-40	5.3	3,5

6.2.1.3.4 Soil chemical and physical properties

The BRU database provides a general information on the dominant soil ecotypes around a certain area. The database does not provide actual soil characteristics on specific sites; therefore, field survey can be crucial. As a result the soil physical properties identified at BALL are shown in Table 6.3. The site is predominantly clay with high clay content of >50% and the change in clay content with depth is little, although as expected, the data is showing some slight increase with depth (Table 6.3). The identified soil physical properties are crucial in irrigation scheduling, a precision agricultural approach to efficiently utilise water resources while controlling environmental pollution as recommended in literature (du Plessis et al., 2017; Odindo et al., 2022b; Ogbazghi et al., 2016; Van der Laan, 2010).

Table 6.3. Soil physical properties for the BALL at three different soil depths.

						Moisture retention	
Soil depth	**Clay**	**Fine Silt**	**Sand**	**Texture Class**	**Bulk density**	**FC**	**PWP**
m	%				kg m^{-3}	$m^3 m^{-3}$	
0.3	51.3	16.3	32.4	Clay	1.1	0.36	0.21
0.6	55.7	16.7	27.6	Clay	1.1	0.36	0.21
0.9	59	17	24	Clay	1.1	0.36	0.21

*Clay has particles <0.002 mm, fine silt has 0.02-0.002 mm and sand has 0.02-2 mm, FC=Field capacity, PWP=Permanent wilting point

The soil chemical properties at three different soil depths are reported in Table 6.4. Most soil chemical properties did not significantly (P>0.05). Significant differences (P<0.05) were only reported for organic C and Ca with depth.

Table 6.4. Mean squares for the soil chemical properties at BALL site, reported for three different depths (0.3, 0.6 and 0.9 m).

Source of variation	Org. C	N	Clay	P	K	Ca	Mg	Exch. acidity	Total cations	Acid sat.	pH (KCl)	Zn	Mn	Cu
	%			mg kg^{-1}	Cmol$_c$ kg^{-1}					%		mg kg^{-1}		
Replication	0.26	0.0027	0.0027	74	1.71	1.5	0.2	0.0004	5.8	1.00	1.00	254	389	9
Soil Depth	0.57*	0.0019	0.0019	85	0.07	2.3*	0.1	0.00004	2.6	0.07	0.07	162	8	1
Residual	0.06	0.0003	0.0003	40	0.03	0.2	0.1	0.00013	0.5	0.03	0.03	101	81	2
Total														

*The asterisk * denotes significant difference (P<0.05) at 5% level

There was a general decrease in soil organic C and Ca content for the soils at BALL (Figure 6.1). This expected in every soil profile due to higher litter content in the topsoil and its reduction as we go deeper the profile. High organic C in the topsoil is important for biological activities controlling nutrient dynamics and is one indicators of soil health.

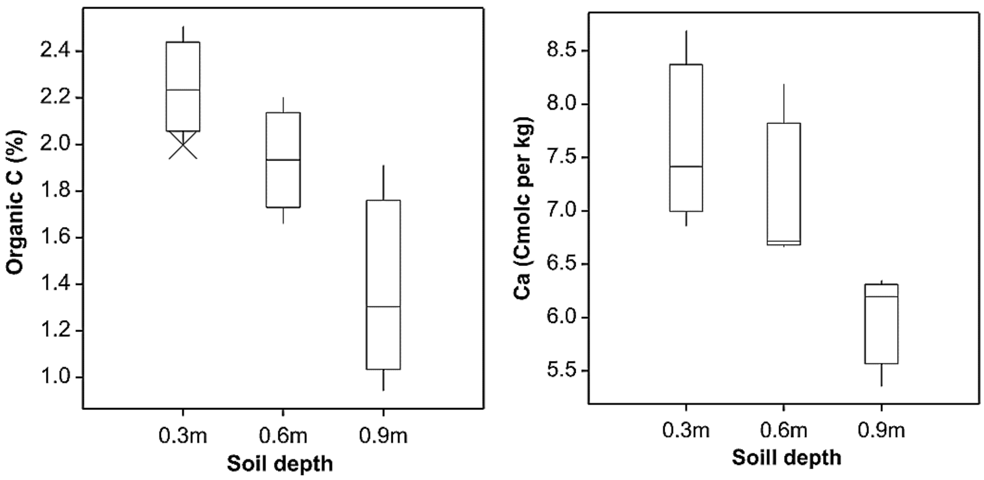

Figure 6.1. Boxplots for soil organic C and Ca content at three soil depths (P<0.05), n=3.

6.2.1.3.5 Irrigation water quality

The suitability of the borehole water for irrigation water quality was assessed (Table 6.5) as suggested in Section 3.3.2.1. The water falls under the class C2-S1 which according to DWS (1996) refers to moderately saline water that can be used for irrigation without any negative impacts. Most importantly faecal contamination pathogens were not detected in borehole water as is the case in some reported groundwaters (Mamera et al., 2021; Masindi and Foteinis, 2021; Ngasala et al., 2021). This is an indicator that there are not pit latrines around the site and the water can be safely used for unrestricted irrigation. Even some heavy metals were not detected because these are usually introduced through industrial activities and these are not found close to BALL.

Agricultural use of human excreta materials is an alternative way to prevent pollutants into the environment and protect the public health. In this case changes in borehole water quality will be monitored from activities occurring at a landscape level. The freedom of pollutants from borehole water is beneficial for encouraging community agriculture. As discussed in Section 3.3.2.1 the installation of boreholes powered by solar energy is a sustainable climate smart solution for communities and this should be considered.

Table 6.5. Physical, biological and chemical properties of borehole water at Bishopstowe Agroecological Living Lab and its suitability for agriculture.

Property		Value
E.C. (mS m^{-1})		30.47
	pH	7.72
	Na	0.56
	Ca	1.18
	Mg	0.72
Cations (me L^{-1})	K	0.01
	Cu	nd
	Mn	0.58
	Fe	nd
Micro Elements (mg L^{-1})	Zn	nd
	Total Alkalinity	2.8
Anions (me L^{-1})	Cl	0.3
	SAR	0.57
Class of Water		C2-S1
E. coli	MPN/100 ml	nd

*MPN; most probable number

6.2.2 Dryland crop production

6.2.2.1 Introduction

In cognisance of challenges threatening local food systems through poor fertility, biodiversity loss, unsustainable agricultural practices and water scarcity, exacerbated by climate change from uncontrolled emissions of greenhouse gases, it is imperative to shift our traditional paradigms. Transitioning to sustainable food systems may take an agroecological approach as propounded by the high level panel of experts from the Food and Agriculture Organisation (FAO) (Wezel et al., 2020). There are 13 agroecological principles that may be applied in parallel or individually in pursuit of sustainable agriculture (Wezel et al., 2020). In this regards these principles include nutrient recycling, input reduction and soil health.

Integration of innovative sanitation technologies with agriculture for resilient food systems can take an agroecological pathway. Whereby transformative approaches, recognising indigenous knowledge systems, enabling environment and appropriate technologies to inter-tackle challenges faced in the target society may be applied. Thus, a field study was done to investigate the potential of using human excreta materials as soil conditioners and fertiliser for crop production under dryland agriculture and their environmental impacts. The study specifically investigated the effects human excreta derived co-compost and urine on (i) crop yield, (ii) soil health, and (iii) potential groundwater contamination under dryland farming.

6.2.2.2 Materials and methods

6.2.2.2.1 Experimental design

The study was conducted at BALL. Twenty-five plots of 12 m^2 (3 x 4 m) were laid out in a randomised complete block design with five treatments and four replicates (Figure 6.2). The treatments were co-compost + urine; T1, poultry manure; T2, urine; T3, no fertiliser; T4 and conventional fertiliser; T5. The co-compost used during the study was made from mixing one part sewage sludge from Ixopo Wastewater Treatment Plant with three parts of green organic waste from various garden service providers in Pietermaritzburg. In this context the co-compost was presumed to improve soil properties such as good moisture and nutrient retention capacity and provide some plant nutrients. The urine used was obtained from the Durban Fresh market public urinal courtesy of Asiye eTafuleni (AET). Urine was used to supplement plant mineral nutrients that could not be obtained from the co-compost. The negative control (T4; no fertiliser application) and positive control (T5; conventional fertiliser application) were included to verify the fertiliser value of the selected human excreta derived fertilisers. The poultry manure was used because it was identified during the participatory exercise as one of the organic fertilisers used by local farmers in farms and there are poultry activities taking place at BALL (Figure 3.8 and Figure 3.12).

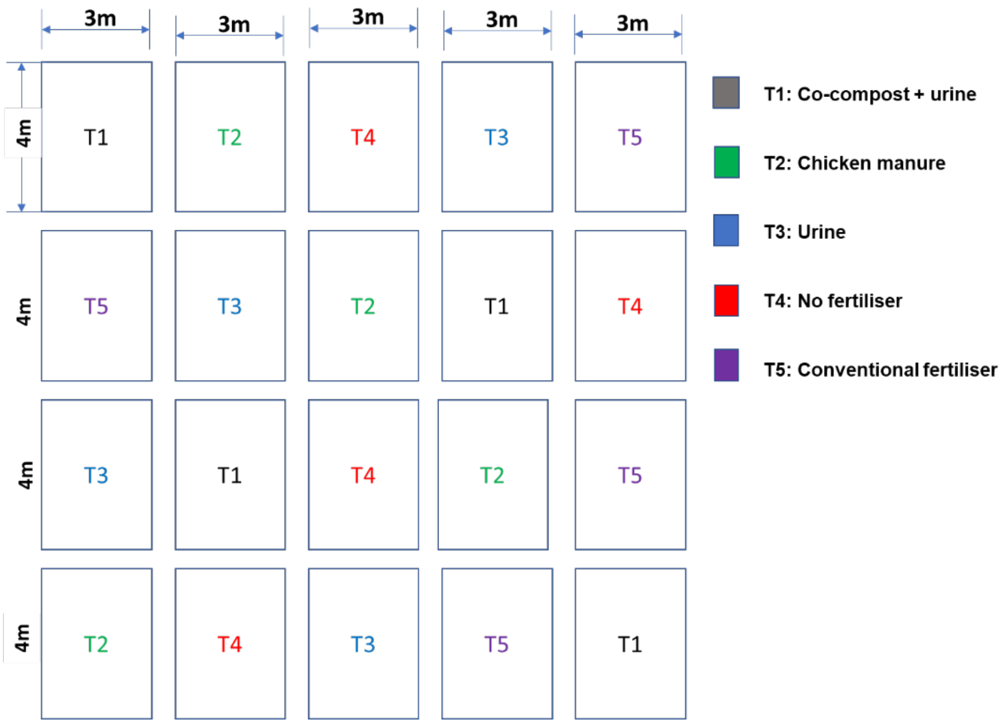

Figure 6.2.Experimental layout showing 25 plots for chilli crop in a randomised complete block design (n=4) and five fertiliser treatments.

The general physicochemical characteristics of co-compost, urine and chicken manure used during the study are shown in Figure 6.3.

Table 6.6. Physicochemical characteristics of materials used during the study.

Characteristic	Compost	Urine	Chicken manure
pH	6.3	8.8	6.1
Moisture (%)	31.2	95	39.8
Total C (%)	20	-	21
Total N (%)	1.2	0.2	5.5
Phosphorus (%)	0.5	0.01	2.2
Potassium (%)	0.3	0.08	2.3
Calcium (%)	1.3	0.0014	10.6
Magnesium (%)	0.2	0.003	0.9
Sodium (%)	0.07	0.01	4700
Copper (mg kg^{-1})	101.5	-	-
Manganese (mg kg^{-1})	-	-	400
Iron (mg kg^{-1})	-	-	1000
Aluminium (mg kg^{-1})	-	-	600
Zinc (mg kg^{-1})	330	-	500

Studies were done under dryland conditions to mimic agricultural practices done by small scale farmers. During farmer engagements and participatory exercises it was learnt that most farmers do not afford irrigation and do not have boreholes in place. Most of them practice dryland production. The climatic data (rainfall and temperatures) was obtained from the National Aeronautics and Space Administration (NASA) access viewer database (https://power.larc.nasa.gov/data-access-viewer/). The data was used to assess the extent to which the rainfall and temperatures were adequate for chilli optimum growth. The impacts of climate change on rainfall dynamics were assessed by comparing the actual received rainfall with historic monthly mean rainfalls averaged for >30 years. Simple water balances were done by calculating monthly average crop evapotranspiration following Equation 6.1.

$$ET_{crop} = ET_{pan} \times K_c \quad \textbf{Equation 6.1}$$

Whereby the ET_{crop} is the historic average crop evapotranspiration, ET_{pan} is the historic average reference evapotranspiration measured from the class A evaporation pan and K_c is the crop factor value for chilli. A simple water balance was done to assess the sufficiency of rainfall for crop production by subtracting average monthly ET_{crop} from actual monthly rainfall.

The selection of crops was done based on climatic adaptability of the crop, season, familiarity to the farmers, potential for value addition or potential high returns per unit area. Agricultural production systems mapping exercises provided a guide on crops commonly grown by the local farmers. Some of the crops identified from the community, to mention a few, include green maize, potatoes, Swiss chard, cabbages, chillies and tomatoes. Chillies (*Capsicum annuum*) of the variety Star 6604 was selected as a test crop due to its potential for processing into chilli paste and powder as identified during the stakeholder consultation and participatory rural appraisals (Section 3.3.2.2). The use of processing crops aligns with the project vision to integrate small scale processing/value addition as an integral component of sanitation value chain in a CBE. Chillies have low microbial contamination risks as per the WHO guidelines especially when multi barrier approaches are applied (WHO, 2006).

6.2.2.2.2 Soil chemical analyses

Soil samples for chemical analyses were collected within the 0.3 m depth from five different spots within the field and bulked to form triplicates of composite samples. The samples were submitted to FAS for the analysis of organic carbon, cation exchange capacity, nutrients (organic N, mineral N, extractable P, extractable K, Ca, Mg, Cu, Al and Fe), soil salinity, exchangeable Na, pH, acid and base saturation according to the standard methods (Manson et al., 2020). Organic carbon was done following the Walkley-Black chromic acid wet oxidation method (Walkley, 1947). Crop fertiliser requirements for crop such as maize, cabbage and chilli were requested.

6.2.2.2.3 Crop establishment and trial management

A land of 17 x 15.5 m of the 50 x 50 m total land allocated was used for experiments. The land was ploughed and disked a month earlier. Plots of 3 m wide and 4 m length giving an area of 12 m^2 were made using hand hoes. Organic fertilisers (co-compost and chicken manure) were applied based on crop N requirements recommended at FAS. The application rate was calculated as in Equation 6.2 according to methods described by Tesfamariam et al. (2020).

$$\text{Fertiliser application} = \frac{\text{Crop N requirements } \left(\text{kg ha}^{-1}\right)}{\text{Mineralisation rate (\%) x compost N content (\%)}} \quad \textbf{Equation 6.2}$$

In Equation 6.2 the mineralisation rate for the BALL site of 29% was obtained from Ogbazghi et al. (2016) with an assumption that Pietermaritzburg is within the sub humid region. The compost N content was obtained from the FAS analytical results.

Chilli seedlings were transplanted on 17 November 2022 at a plant spacing of 0.5 x 0.5 m. The inorganic fertilisers were applied at recommended rates (Urea; 326 kg ha^{-1}, Single Super Phosphate (SSP); 1 960 kg ha^{-1}, Potassium Chloride (KCl); 558 kg ha^{-1}) which directly translated to 150:196:290 (N:P:K). The urea was split applied while SSP and KCl were applied once off. The fertilisers were banded followed by covering up with soil to prevent volatilisation. The urine was collected and used after storage for one month at room temperature. The application was done according to methods by Jönsson et al. (2004) as recommended by Odindo et al. (2022b). The stored urine N content value of 3.9 g L^{-1} obtained from previous studies (Odindo et al., 2022a) was used to calculate crop N requirements following Equation 6.3.

$$\text{Urine (L m}^{-2}\text{)} = \frac{\text{Crop N requirement (g m}^{-2}\text{)}}{\text{N content in urine (g L}^{-1}\text{)}} \quad \textbf{Equation 6.3}$$

The urine was diluted with water at a ratio of 3:1 and applied directly to the plant surface using the watering container to avoid foliar contact as recommended by Richert et al. (2010). The soil was covered soon after application to minimise volatilisation losses. An integrated weed, pest and diseases management program was implemented. The selected chilli variety has a general tolerance to leaf diseases however no chemicals were used to control pests and diseases since they were not identified.

6.2.2.2.4 Soil health determination

About 200 g of soil were sampled from the 0.3 m topsoil level and around the 0.1 m radius of the plant before planting and after the final crop harvest. Samples were placed in a zip lock plastic at room temperature for not more than five days and submitted to Sporatec Soil Microbiology Laboratories within the Department of Microbiology at the Stellenbosch University for the analysis of microbial communities and soil enzymatic. The microbial communities were analysed using the molecular fingerprinting technique, which generate a profile for each composite soil sample (Singh et al., 2006). The soil mineral N (NO_3^- -N and NH_4^+-N) was determined using the Thermo Scientific™ Gallery™ Discrete Analyzer after extraction in 2 M KCl (Maynard et al., 2007). N mineralisation, urease activity, β-glucosidase, PO_4^{3-}-P, alkaline and acid phosphatase, microbial activity, organic and active carbon were determined according to standard methods (Karlen et al., 2021).

6.2.2.2.5 Crop yield

The chillies harvesting started from 12 weeks after transplanting. The fresh mass from the harvested chillies was measured immediately using a balance with ±0.02 g accuracy. The yield per harvest was determined following the Equation 6.4.

$$\text{Yield (kg ha}^{-1}\text{)} = \boldsymbol{MA} \times \frac{1\,0000\ (\text{m}^2)}{1000\ (\text{g})} \qquad \textbf{Equation 6.4}$$

Whereby the ***M*** is the mass of chillies in grams per plant. ***A*** is the area per plant refers or plant spacing of 0.5 x 0.5 m (0.025 m^2). The cumulative yield was then determined as a sum of all the three harvested made.

6.2.2.2.6 Groundwater sampling and analyses

Groundwater samples were analysed for suitability as irrigation water and human health safety in accordance with drinking water quality standards. The borehole water samples were collected before planting and after six months. These were submitted to the salinity laboratory of the FAS for the analysis of salinity, Na, Ca, Mg, K, Cu, Mn, Fe, Zn, Total alkalinity, SAR, salinity class and Cl^- according to standard methods. Some samples were analysed for nutrients (N and P) and pathogens (*E. coli*) according to Velkushanova et al. (2021).

6.2.2.3 Data analysis

The GenStat 21th Edition was used to analyse the data. The quantitative data was subjected to the analysis of variance (ANOVA) at 5% significance level. The soil microbial community and biochemical data was subjected to multivariate analysis of variance (MANOVA) at 5% significance level since there were 19 variables to be considered. Where $p<0.05$ the Bonferroni multiple comparison test was done to compare differences amongst the treatments.

6.2.2.4 Results and discussion

6.2.2.4.1 Climatic information

The temperature and rainfall received at BALL over the period of 6 months is shown in Figure 6.3a. The mean daily temperature during the chilli growing period ranged from 10.8°C to 25.1°C. The optimum chilli growing daily mean temperatures for 4 to 5 months period are between 20°C and 27°C and a minimum daily mean temperature of 15°C is ideal (Welbaum, 2015). However, results in Figure 6.3a shows that the mean daily temperature was above 15°C, supporting optimum chilli production.

Although the chilli is a drought tolerant crop with a tap root system that can go as deep as 1 m (Welbaum, 2015), its production under dryland could not prohibit its optimum yield. The result in Figure 6.3b shows that during the chilli growing period, the BALL site received more rainfall in comparison to historical average calculated from the time of over 25 years. On climate change perspective, the site shows to be getting more rain than previous, likely to support dryland production. The actual received rainfall was higher than the calculated crop water requirements for chilli (Figure 6.3b). This means there was no supplementary irrigation required for most of the time.

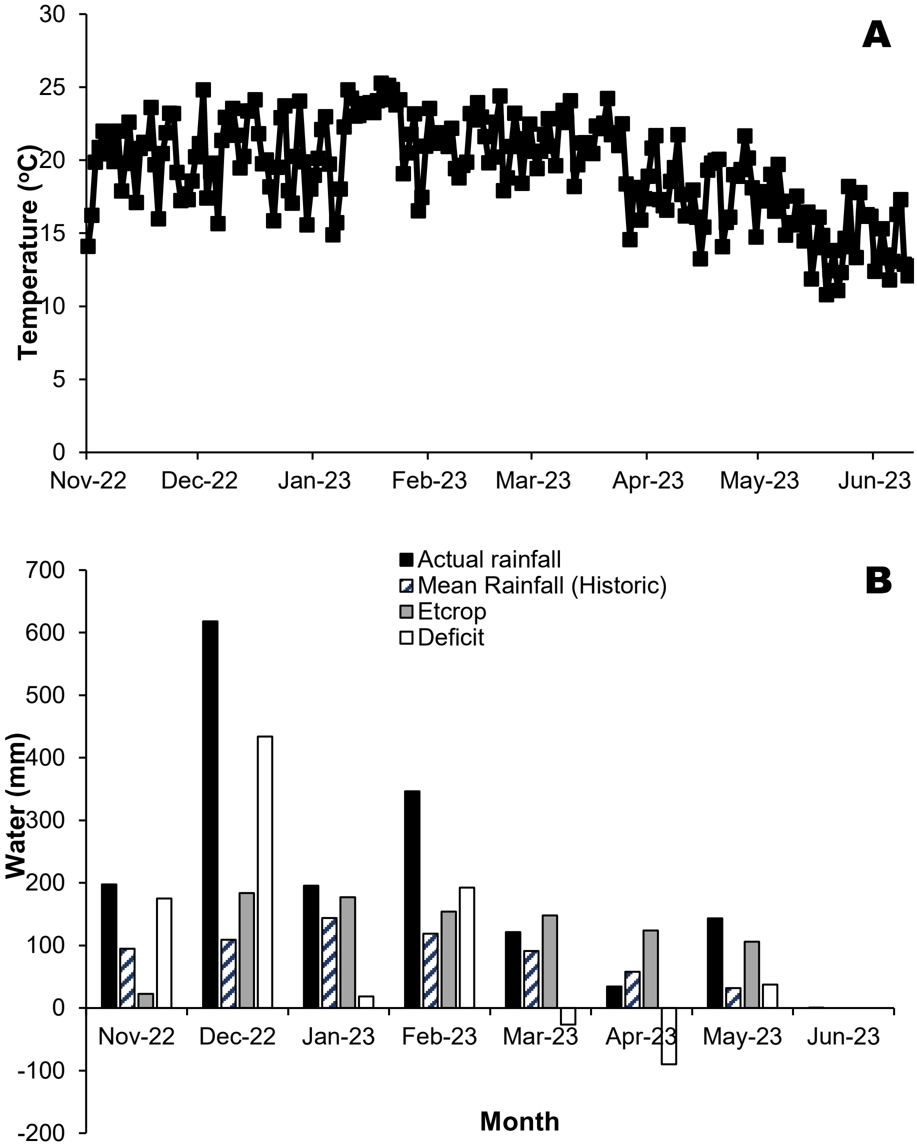

Figure 6.3. The climatic information (Temperature; A and Rainfall; B) for Bishopstowe Agroecological Living Lab for a six-month period (Total rainfall = 1 656 mm).

6.2.2.4.2 Crop yield

The analysis of variance for the chilli yields shows no significant differences in repeated measures for treatments except for the sampling time (Table 6.7).

Table 6.7. Analysis of variance showing repeated measures for chilli yield in five different treatments.

Source of variation	Degrees of freedom	Sum of squares	Mean of squares	Variance Ratio	F probability
Replication stratum	3	0.1	0.0338	0.06	
Replication x subject stratum					
Treatment	4	3.6215	0.9054	1.73	0.207
Residual	12	6.2642	0.522	1.02	
Replication x Subject x Date stratum					
Degrees of freedom correction factor 0.6833					
Date	2	4.5064	2.2532	4.4	0.038
Date x treatment	8	7.1206	0.8901	1.74	0.167
Residual	30	15.3685	0.5123		
Total	59	36.9826			

Due to high variance in the yield data caused by outliers, median values were used to explain the treatment effects (Figure 6.4a). The median values for the chilli yields show to be almost similar across all treatments including the control. Indicating that the site inherent fertility was sufficient to support chilli growth. Co-compost is a soil conditioner which does not show immediate effects on yield increase compared to inorganic fertilisers. Even some studies using biochar showed that its effects are visible after some period of application (Fendel et al., 2022). In this case the co-compost was applied at 20 tons per hectare which is double the conventional application rate. This was done in consideration of mineralisation rate to increase crop bioavailable N as recommended by Tesfamariam et al. (2020). Meaning that N was not a limiting factor in co-compost amended chillies and there was supposed to be a noticeable difference with the control. Khaitov et al. (2019) tested the effects of different livestock composted manure grown in high clay soil (>50% clay) on chilli yield. The authors reported increased yields at single and double application rates in comparison to the control.

Significant differences in yield reported over time were caused by an outlier value in the control treatment on the second harvest (28/03/2023) see Figure 6.4. Otherwise the control did not outperform co-compost in terms of chilli yields.

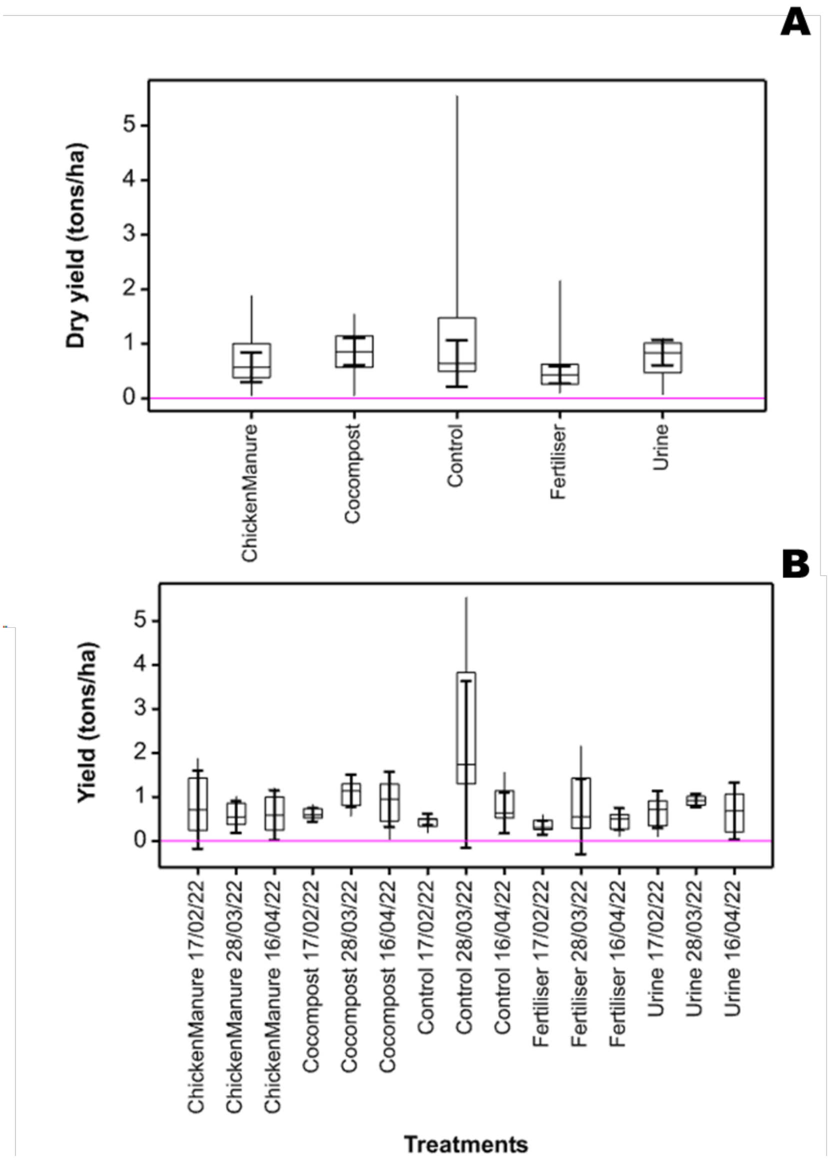

Figure 6.4. Boxplots (showing median values, 25-75% quartiles and non-parametric standard error of median, n=4) for chillies yield over the three harvesting months (1; February, 2; March and 3; April) (A) and five treatments showing treatment differences and treatment differences over time (B).

As discussed from the previous section nutrients were not limiting, the N was applied at recommended rates for all amendment treatments. In this study N was in adequate supply for optimum chilli yields. Although the rainfall was sufficient to promote optimum growth for chillies as discussed in previous sections it is imperative to discuss if dryland conditions played a role. Irrigating crops giving a room for rainfall increase chilli yield especially if fertiliser is adequate. Studies by Girmay and Wale (2019) showed that irrigating chillis at five day interval, recharging the soil field capacity yielded about 9 tons/ha while farmer irrigation practices were around 5.4 tons/ha. The cumulative median values for chilli yield were as low as 4 tons/ha (fertiliser treatment) and as high as 6 tons/ha (chicken manure) (Figure 6.5), which are not very different from the values obtained under irrigated and well managed conditions. A crop modelling study using the SWB Sci model done by Abebe (2010) showed that the harvestable dry mass for the same chilli variety ranged from 4 to 5.8 tons/ha. They further validated their results with empirical findings and reported 2.11 to 3.68 tons/ha of dry yield. In South Africa dry chilli yields of between 1.5 tons/ha (conservative conditions) to 4 tons/ha (target) are expected (KZNDARD, 2019). This further confirm that dryland chilli production was not negatively affected by amounts of rainfall received. Further confirming that chillies are climate smart crops.

Higher yields could have been obtained if green chillies were considered. According to the South African DALRRD production guideline, chillies attain higher yields if harvested frequently at 10–14-days interval. Harvesting green chillies stimulates flowering and more yields (KZNDARD, 2019). They further reported that chilli yields are lower when waited to attain red colour and harvesting is delayed. During the study only red chillies were harvested at a monthly interval for three months. Meaning that higher yields could have been attained irrespective of treatment applied.

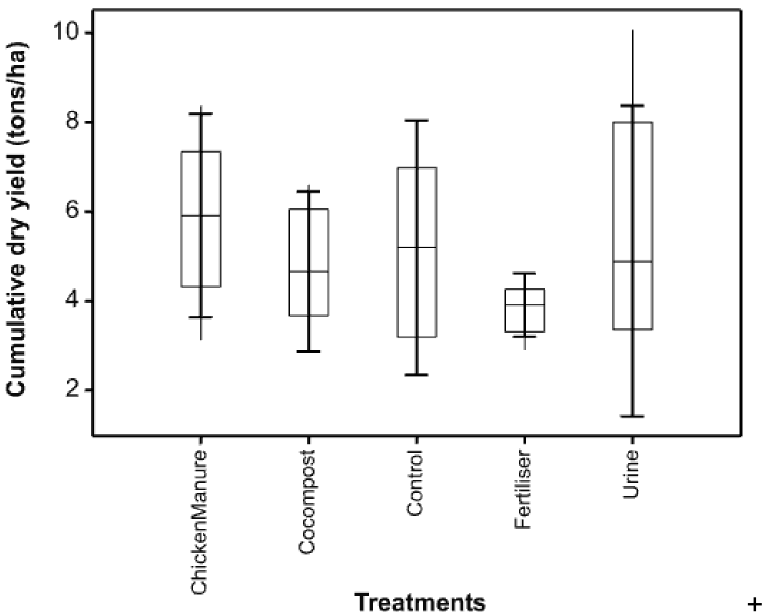

Figure 6.5. Cumulative chilli yield shown by boxplots (showing median values, 25-75% quartiles and non-parametric standard error of median, n=4) for three monthly harvests.

6.2.2.4.3 Soil health

The use of organic amendments alters soil ecological environment as well as microbial activities. Changes in pH, moisture content and introduction of xenobiotics may affect the microbial activities which drive nutrient cycling and organic matter degradation as well as soil nutrients and subsequent crop yields (Urra et al., 2019). From the study, the amendments did not significantly change most parameters of soil health except for organic C, extractable P and microbial activity, which significantly differed at 5% level Table 6.8.

Table 6.8. Mean squares for soil health with regards to biochemical analyses and microbial communities amongst different fertiliser amendments (n=4).

Source of Variation	DF	Missing value	Soil Moisture	Organic C	Electrical Conductivity	pH (water)	NO_3	NH_4	Nmin $-NH_4$
Replication	3		0.001	0.03	700	0.6	8.4	17	0.2
Treatment	4		0.0004	**0.11***	2117	0.02	21	12	1
Residual	11	-1	0.001	0.03	6015	0.1	47	40	1
Total	18								
Source of Variation	**DF**	**Missing value**	**Bacterial Shannon index**	**Bacterial Simpson's index**	**Bacterial Species richness**	**Fungal Shannon index**	**Fungal Simpson's index**	**Fungal Species richness**	**P (Bray II)**
Replication	3		0.13	0.005	17	0.09	0.001	37	3500
Treatment	4		0.02	0.002	2	0.06	0.002	27	**9800***
Residual	11	-1	0.74	0.01	190	0.2	0.004	57	2700
Total	18								
Source of Variation	**DF**	**Missing value**	**Active Carbon**	**Acid Phosphatase**	**Alkaline Phosphatase**	**Urease**	**β-Glucosidase**	**Microbial Activity**	
Replication	3		3939	75505	473571	30	4500	3067	
Treatment	4		14059	97282	74081	21.4	7740	**17359***	
Residual	11	-1	4308	161853	198323	8.2	6134	3246	
Total	18								

*Significant differences at 5% level

The differences in organic C and microbial activity are reported in Table 6.9 (a) and (b). Comparisons done showed differences in organic C between control vs co-compost + urine (Table 6.9a). Higher organic C in co-compost + urine compared to the control was caused by the carbon content in co-compost as mentioned in literature (Fendel et al., 2022; Fuhrmann et al., 2022). Although co-compost increased organic carbon the microbial activity was significantly lower than chicken manure (Table 6.9b). The application of organic amendments such as organic waste compost can increase soil microbial activity compared to fertiliser application (Elbl et al., 2019; Fuhrmann et al., 2022). Since co-compost amended soil had high organic C microbial activity was supposed to increase. Meaning that other factors could have played a role. Martín-Lammerding et al. (2021) mentioned poor rainfall patterns as limitation to microbial activity. In this case monthly rainfall was adequate to support crop growth and soil recharge (Figure 6.3). Even if rainfall could play a role all the treatments were supposed to be affected. High microbial activity in chicken manure was caused by using fresh manure which was not stabilised. This corroborates with findings by Urra et al. (2019) who reported that fresh chicken manure can increase microbial activity compared to stabilised organic amendments. Although not significantly different to co-compost, the control had a relatively higher microbial activity value which was not significantly different to chicken manure.

Treatments with urine and inorganic fertilisers generally had lower microbial activity compared to the non-amended (control) and the chicken manure. Negative impacts of inorganic fertilisers on microbial activity have been reported. Elbl et al. (2019) reported a >25% decline in microbial activities in the soil amended with inorganic fertilisers compared to the one that has not been applied any fertilisers. The application of urine in co-compost could have triggered microbial stress. Microbial stress is defined as the ability of microorganism to adapt to adverse conditions such as pH, temperatures and other extreme conditions (Abdul Rahman et al., 2021). However, some microorganism may succumb to their inability to synthesise proteins that help them adapt to environmental stresses. Increased soil microbial stress in response to application of cow urine was also reported by Bertram (2009). From the current study it can be deduced that application of inorganic fertiliser affected microbial activity under dryland conditions. The effects of prolonged drought on reduced microbial activity was also explained by Hueso et al. (2012). Microbial activity takes place in the top 50 mm of the soil where conditions are aerobic. These processes are lower in low moisture content. Low moisture content could have played a role since there was no irrigation maintaining high water content in the top 100 mm from which sampling was done. Even the soil moisture content in the samples was very low (Figure 6.6). Meaning that irrigation is crucial to keep maximum microbial activity for nutrient cycling and organic matter degradation processes. This further support the importance of having water supply in the form of a borehole to supplement rainfall for sustainable agriculture in low-income communities.

Table 6.9. Treatment comparisons (a) and mean values (b) for organic carbon and microbial activity.

a) Comparisons	**Significant (95% significance level)**	
Comparison	**Organic C**	**Microbial activity**
Control vs Fertilizer	no	no
Control vs Urine	no	no
Control vs Chicken manure	no	no
Control vs Co-compost + urine	**yes**	no
Fertilizer vs Urine	no	no
Fertilizer vs Chicken manure	no	**yes**
Fertilizer vs Co-compost+ urine	no	no
Urine vs Chicken manure	no	**yes**
Urine vs Co-compost + urine	no	no
Chicken manure vs Co-compost +urine	no	**yes**

b) Bonferroni tests	**Means (n=4)**	
Treatment	**Organic C (%)**	**Microbial activity (mg fluorescein·kg^{-1} soil·3h^{-1})**
Control	0.66^{a}	92.2^{ab}
Fertilizer	0.73^{ab}	25.5^{a}
Urine	0.75^{ab}	38.3^{a}
Chicken manure	0.81^{ab}	185.5^{b}
Co-compost + urine	1.10^{b}	42.3^{a}

Phosphorus exists in various forms in the soil. It can either be organic bound, in solution or adsorbed on the soil colloids. The extractable P is the one that is adsorbed on soil colloids. The median values for extractable P were generally high in co-compost and chicken manure compared to other amendments. This is attributed to relatively high P concentrations in organic amendments (Table 6.6). Several studies have confirmed that the P in untreated urine is generally lower than N and K and these are lower than in an inorganic fertiliser (Alemayehu et al., 2020; Jönsson et al., 2004; Richert et al., 2010). Very low extractable P in soils that was applied an inorganic fertiliser resulted from solubility of SSP applied, uptake by plants or loss from the topsoil. Organic matter increases the surface area for soil adsorption capacity, allowing soils to capture and return inorganic phosphates. This explains why the urine and inorganic fertiliser treatments had lower extractable P median values. The ability of organic amendments such as co-compost and biochar to improve nutrient retention by creating adsorption sites that retain cations and anions is well documented and recommended on an environmental and agronomic perspectives (Fuhrmann et al., 2022; Snyman et al., 2006; Urra et al., 2019). The only challenge is when phosphorus is transported to nearby water bodies through surface runoff and cause pollution if improper slope management strategies are put in place (Sharpley, 2016). In this case the site is moderately susceptible to erosion.

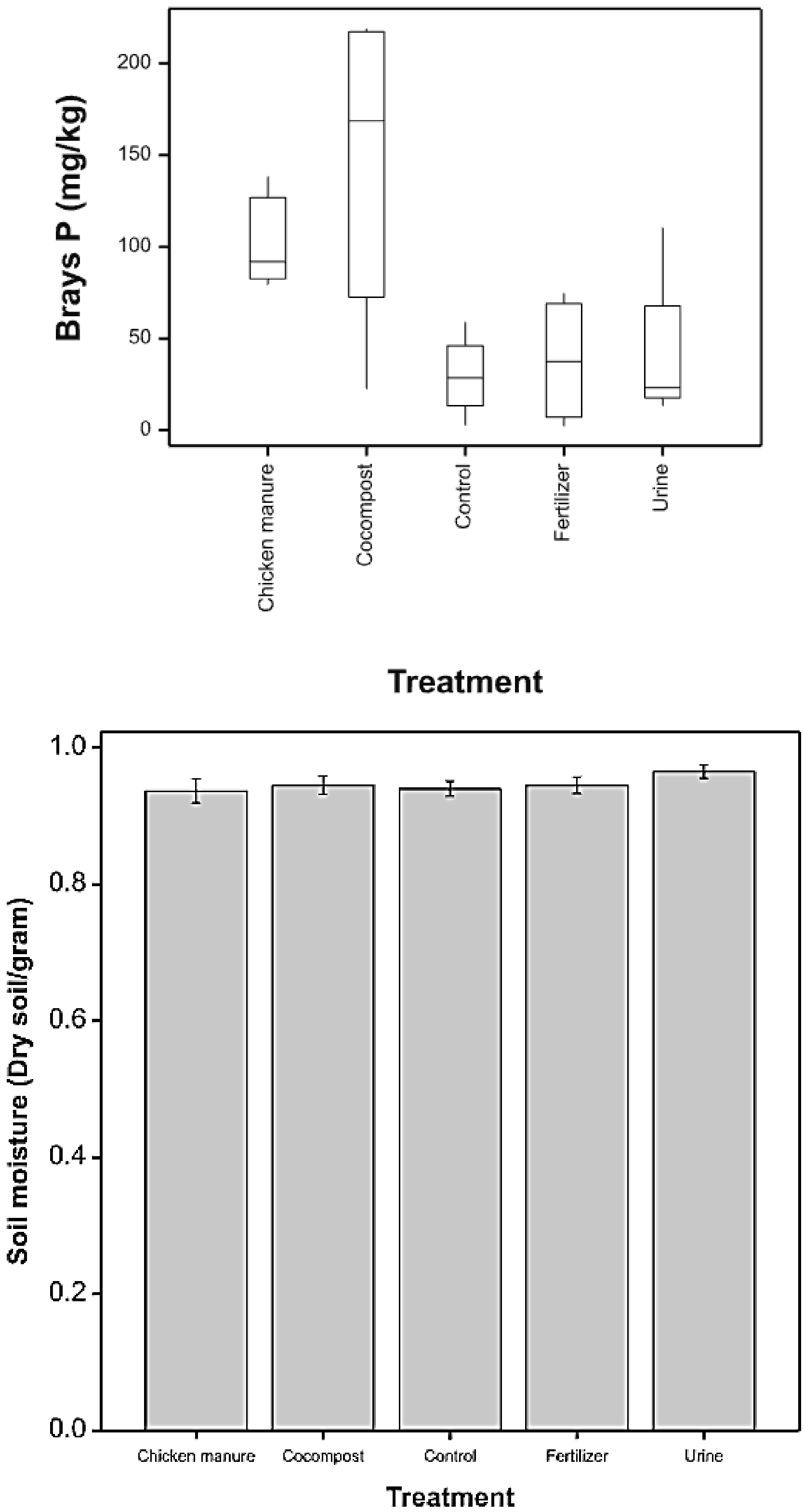

Figure 6.6. Boxplots showing median values and 25-75% interquartile ranges for extractable P (Brays P) concentrations in five fertiliser amendment treatments (n=4) and the histogram showing soil dryness per sample analysed.

6.2.2.4.4 Groundwater contamination

The protection of groundwater resources from anthropogenic activities is of utmost importance. In consideration of widely blame of pit latrines on contaminating borehole water leading to disease outbreaks, water samples monitored on a six-month interval just to cross check potential contamination from applied amendments showed no significant change in *E. coli* and nitrate concentrations (results not shown).

6.2.2.5 Conclusions and recommendations

6.2.2.5.1 Conclusions

The study tested the application of best agricultural practices on the use of HEDFs based on farmer production systems identified during participatory exercises. In this case chilli production was assessed under dryland farming. The monitored climatic conditions did not prohibit the production of chilli pepper. The chilli yields in all fertiliser amendments were comparable with the non-amendment (control). Most aspects of soil health; microbial communities, microbial enzymatic activity and soil chemical analyses did not significantly differ in response to amendments except for microbial activity, organic C and extractable P. Microbial activity was significantly high in chicken manure amendments. The organic C and extractable P significantly increased in co-compost. Dryland production limits soil microbial activity for nutrient cycling. The extractable P was higher in both co-compost and chicken manure. Lastly, the pathogens and mineral nutrients (N and P) were not detected in the nearest borehole water samples over the six-month period, implying that the existing activities did not affect the groundwater.

6.2.2.5.2 Recommendations

- With the current systems small scale farmers can produce adequate chillies during the summer periods because the climatic conditions are not limiting. The challenge comes in winter when they must meet market demands. It is crucial for them to invest in irrigation systems so they should be guided in ways to obtain infrastructural development loans from organisations such as ADA as one of the considerations in promoting resilient circular bioeconomy.
- The full potential attributes of human excreta derived fertiliser could not be expressed in dryland agriculture. Therefore more research should be done to understand the impacts of HEDFs on soil health under irrigated cropping systems as part of science and innovation in optimising management systems in a circular bioeconomy. In addition the soil health impacts in terms of microbiome shifts, nutrient cycling and emissions can be assessed in the long term.

- Organic amendments such as co-compost are good sources of soil bioavailable P even in dryland agriculture but caution must be given in managing pollution from surface run off especially in clayey soils in sloping areas.
- On the sanitation safety point of view the amendments did not cause groundwater contamination as per the hypothesis code PPL6 of Figure 4.1. However, long term monitoring is still needed.

6.3 Input supply studies: the use of human excreta derived materials for food crop seedlings production.

6.3.1 Introduction

High cost of inputs such as planting materials is one of the challenges on the input supply part of the food production systems. In a motive to establishment of resilient food systems before a circular bioeconomy, Baiphethi and Jacobs (2009) suggested that farmers should be trained on exploring income generation activities to finance purchases of improved inputs. The same has been suggested in Section 3.4. Low input costs of high value crops such as vegetables promote sustainable and resilient food systems. These do not only provide income for household food security but extra benefits such as nutritional security (Mwadzingeni et al., 2021).

Despite challenges faced by different actors across the food and waste value chains, there are unrealised interlinkages which might provide opportunities for maximising associated benefits. For example, the use of wastewater for food crops production is limited by health risks while there are opportunities to use it for seedlings and ornamentals production (see hypotheses PCD6 to PCD8 in Figure 4.1). In addition, the market for co-compost is a challenge for small scale communal farmers who cannot produce at economically viable scale as reported in Section 5.4. In cognisance of value addition through co-compost fortification, there is an opportunity for further value addition to suit financially viable small scale compost production. In this case upcycling co-compost as a seedling growing media may be considered.

Studies on the utilisation of human excreta for seedling production have been done using various wastewater and compost variants, various results being reported (Divya et al., 2015; Khaleel et al., 2013; Rekik et al., 2017). This has not been done with domestic treated wastewater, e.g. from the DEWATS. The use of pine bark and goat manure co-compost increased seedling growth when used as a growing media (Mupondi et al., 2010). Meaning utilisation of human excreta derived co-compost as growing media and DEWATS effluent as irrigation water provides an opportunity for sustainable waste management as well as food production as hypothesised at PCD6 and PSS3 (Figure 4.1). This study investigated the potential of DEWATS effluents and sewage sludge derived co-compost for vegetable crops seedling production and their compliance with the best practices required by the Seedlings Growers Association of South Africa (SGASA) as per the South African legislation. The study addressed three research questions, which were: (i) Do the sewage sludge derived co-compost meet the SGASA standard requirements for seedling production, (ii) To what extent can HFCW and AF effluents (DEWATS effluents) be used for vegetable seedlings production without negatively affecting seed germination and seedling vigour and (iii) Do the seedlings irrigated with DEWATS effluent under sewage sludge derived co-compost growing media comply with the SGASA best practices in terms of plant diseases and enteric pathogens risks on workers in accordance with the South African Occupational Health and Safety Act, 1993 (Act No. 85 of 1993).

6.3.2 Materials and Methods

6.3.2.1 Experimental site and material

Greenhouse and laboratory experiments were conducted at Newlands Mashu research site and the UKZN Plant Sciences in Pietermaritzburg. Details of Newlands Mashu study site are reported in Section 3.3.1.3. The co-compost produced from municipal green waste and sewage sludge from wastewater treatment plant (WWTP) was used as growing media for seedling production. Co-compost is a mixture of one or two feedstocks which provide N and C source to hasten microbial activity during thermophilic aerobic composting process (Cofie et al., 2016). Details on the co-compost used are reported in Section 5.2.1.

6.3.2.2 Characteristics of co-compost as new growing media

The SAGSA recommends that growing media used for seedling production should comply with the South African Fertiliser, Farm Feeds and Agricultural remedies and Stock Act of 1937
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(DALRRD, 2017). It must meet the standards for a group two fertiliser in terms of supporting up to 80% seed germination. Therefore, germination percentages of seeds within the media were measured. Three subsamples of mature, stabilised and sieved co-compost were sampled from a pile. The three subsamples were collected from three different spots of the piles at varying depths (300 mm, 600 mm and 900 mm) and bulked to form a homogenised sample. About 200 mL volume of co-compost was collected, submitted to FAS where it was screened for soil borne root diseases using the bait method according to Watanabe et al. (2008) methods. Growing media samples were tested for pathogens: *Pythium*, *Phytophthora* and *Rhizoctonia*. 200 g of the medium was decanted onto a sterile 5 L container with 2 L sterile water, adding popcorn baits for *Pythium* and leaves of camellia, lemon and rhododendron for *Phytophthora* detection. Sterile toothpicks were added to the remaining medium samples for

the detection of *Rhizoctonia* sp. Popcorn baits were later plated on PYD (*Pythium*-selective medium), leaf baits on *Phytophthora* selective (PARPH) medium and popcorn baits on *Rhizoctonia*-selective KHP medium. Later, baits where fungal growth was observed were ground for DNA extraction; PCR analysed using *Pythium*-specific Cox1_pyth F1/R1 primers and *Phytophthora*-specific YPh1F/YPh2R primers. Positive amplicons were further sent to Inqaba Biotec for Sanger sequencing for identification of detected species.

6.3.2.3 Effects of DEWATS effluents on seedling emergence and growth

Controlled greenhouse experiments were laid out in complete randomised design (CRD) with three treatments (AF effluent irrigation, HFCW effluent irrigation and tap water irrigation) replicated three times in each seedling tray. Three vegetable seeds (Swiss chard; *Beta vulgaris*, Onion; *Allium cepa* and tomato; *Solanum lycopersicum*) were planted in each third space of the seedling tray. The three crops were selected for various reasons; onion and Swiss chard are common food security crops consumed in many South African communities. Tomato is a crop that can be processed into tomato sauce.

The seedlings were irrigated at a three-day interval using sprinkling watering cane. Seedling height was measured following methods by Issoufi et al. (2006). Chlorophyll content was measured using the CCM 200 chlorophyll meter (Shibaeva et al., 2020). The seedling emergence percentage was recorded on a weekly interval as shown in Equation 6.5:

$$\text{Emergence percentage} = \frac{\text{number of seedlings emerged}}{\text{Total seeds planted}} \times 100$$ **Equation 6.5**

Seed vigour is defined as the sum of properties of the seed which determines the level of activity of a seed from germination to seedling emergence (Gupta, 1999). Therefore, it encompasses all aspect of seedling growth rate, hence, seedling dry mass was measured. Three seedlings per replicate were harvested six weeks after planting and oven dried at 60^{o}C for 72 hours and dry mass measured using a balance at a 0.01 g accuracy.

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The seedling compliance parameters according to the SGASA standards include seedling pathogens (*Pythium spp., Fusarium spp., Fusarium spp.* and *Phytophthora spp.*). These were analysed on tomato plants only. Six seedlings were collected per each replicate, bulked to form a composite sample, wrapped in newspaper and packaged in another bag or box. The samples were submitted to FAS for the analysis of the above-mentioned pathogens using the baiting method, testing positive were subjected to Polymerase Chain Reaction (PCR) test followed by Deoxyribonucleic Acid (DNA) sequencing of the PCR amplicons to confirm the pathogens.

6.3.2.4 Seedlings safety for handling

One of the reasons behind producing seedlings using DEWATS effluent is to minimise pathogen contamination risks on final product to be consumed raw (See PSS3 and PCD6 in Figure 4.1). On the other hand part of the sanitation safety plan is to minimise pathogen exposure risks to workers handling plants irrigated using wastewater as part of compliance with the SGSA best practices which recognises the Occupational Health and Safety Act No. 85 of 1993. As a result, the concentrations of *E. coli* was analysed on the seedlings above ground biomass following methods described by Jensen et al. (2013). About six samples of seedlings above ground cuttings were cut using a sterile disposable scalpel blade from each replicate, bulked to form a composite sample and packed in sterile plastic containers. The samples were analysed for *E. coli* at WASH R&D research laboratory according to standard methods (Velkushanova et al., 2021). The risk reduction level was quantified based on changes in *E. coli* concentration from wastewater to plant tissues and seedling media as shown in Equation 6.6.

$$\text{Pathogen transfer rate} = \frac{\mathbf{P}\left(\frac{\text{cfu}}{100\ \text{mL}}\right) \mathbf{+M}\left(\frac{\text{cfu}}{100\ \text{mL}}\right)}{\text{Effluent}\left(\frac{\text{cfu}}{100\ \text{mL}}\right)} \times 100 \qquad \textbf{Equation 6.6}$$

Whereby cfu is the colony forming unit, **P** is the plant tissue *E. coli* and **M** is the soil media *E. coli* and effluent is the concentration of *E. coli* in irrigation water source.

6.3.3 Results and discussion

6.3.3.1 The effects of DEWATS effluent on seed germination and seedling vigour

The effects of DEWATS effluent in combination with co-compost on seedling emergence are shown by the analysis of variance table (Table 6.10). The tomato seedling emergence significantly differed between the growing media and irrigation treatments over the study period (P>0.01).

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Table 6.10. The analysis of variance table showing mean squares for the repeated measures made on seedling emergence amongst three test crops.

Source of variation	Degrees of freedom	Onion	Swiss chard	Tomato
Replicate stratum	2	1739	56	520
Replicate and Subject stratum				
Media	1	17	270	25
Water	2	392	51	167
Media*Water	2	1317	673	224
Residual	10	885	737	262
*Replicate*Subject*Time stratum*				
Degrees of freedom correction factor 1				
Time	4	30739***	1991***	1769***
Time*Media	4	2	102	13
Time*Water	8	35	65	58*
Time*Media*Water	8	154	35	87**
Residual	48	106	47	18
Total	89			

*** Significant difference at 0.1% level, **Significant difference at 1% level and *Significant difference at 5% level

Seedlings emergence rate was relatively higher in tomato seedlings irrigated with tap water in the conventional growing media (Figure 6.7) . The AF effluent and co-compost followed while others were relatively lower. Seedling emergence is a some of processes starting from the germination until the plant emerge out of soil. This is affected by oxygen, temperatures, inherent seed dormancy, moisture content and sometime chemical properties such as pH and salinity (Rekik et al., 2017). Meaning that robust seedlings can overcome such conditions and emerge as vigorous plants which when planted in the field establish and grow faster. In simple terms, seedling vigour is a quality indicator of how fast a seedling can emerge and adapt to dynamic external environments. Treated wastewater contains dissolved salts which might alter soil environmental conditions leading to phytotoxicity of sensitive seeds. However, this study proved that that's not the case when using DEWATS effluent as shown by high seedling emergence in AF effluent + co-compost media (Figure 6.7). It should be noted that the AF effluent have not yet undergone planted gravel filters (Section 3.3.1.3). This was confirmed earlier on during studies by Ravindran et al. (2016). Furthermore, an ideal growing media should have good pore size to provide adequate aeration for optimum germination and seedling emergence. Figure 6.7 shows that seedling emergence from the conventional media in other treatments was comparable to co-compost. Thus, showing that co-compost is a good growing media. The fact that the emergence rate graph later flattened at 11 days after planting indicates that the use of DEWATS effluent and co-compost as growing media is comparable to conventional practices.

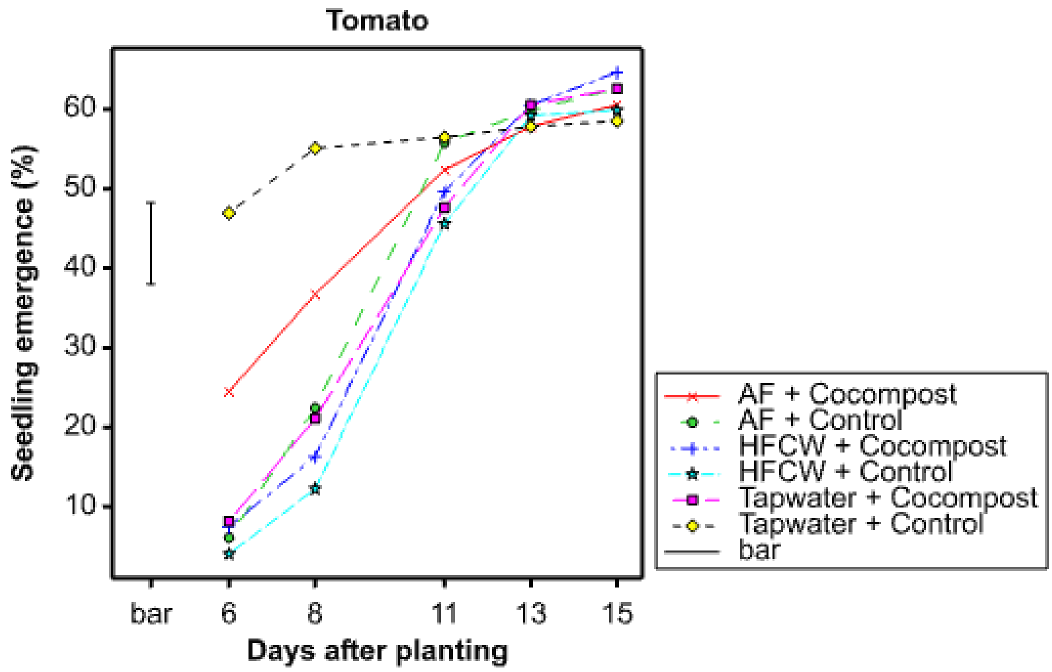

Figure 6.7. Mean values for tomato seedling emergence (%) under various irrigation treatments and growing media for 15 days (n=3, bar is the pooled standard error).

Plant height is another important plant physiological parameter. In this case change in seedling height in response to irrigation treatments and growing media type was measured and results are summarised in Figure 6.8. The tap water + control seedlings had a lower growth rate. The HFCW + co-compost, AF effluent + co-compost and tap water + co-compost treatments had highest seedling growth rate in tomato and Swiss chard seedlings. The onion seedlings showed a different pattern where the HFCW + control performed relatively like all the treatments. All these findings were attributed to the nutrient content in co-compost and DEWATS effluent. After crop emerges, change in seedling height is affected by environmental factors such as photosynthetic capacity and availability of water. In this case, low nutrient concentrations played a significant role as evidenced by low growth rate in tap water + control treatment. The studies showed that co-compost was the major contributor to seedling vigour as evidenced by highest growth rates for tap water + co-compost in Swiss chard and onion seedlings. The same results were reported by Nartey et al. (2017) who found that faecal sludge based co-compost can increase seedling plant height. Furthermore, all the DEWATS effluents (HFCW and AF effluents) had high growth rates when grown in co-compost growing media. Meaning that a combination of DEWATS effluent and co-compost provide more vigorous seedlings than when grown in conventional growing media.

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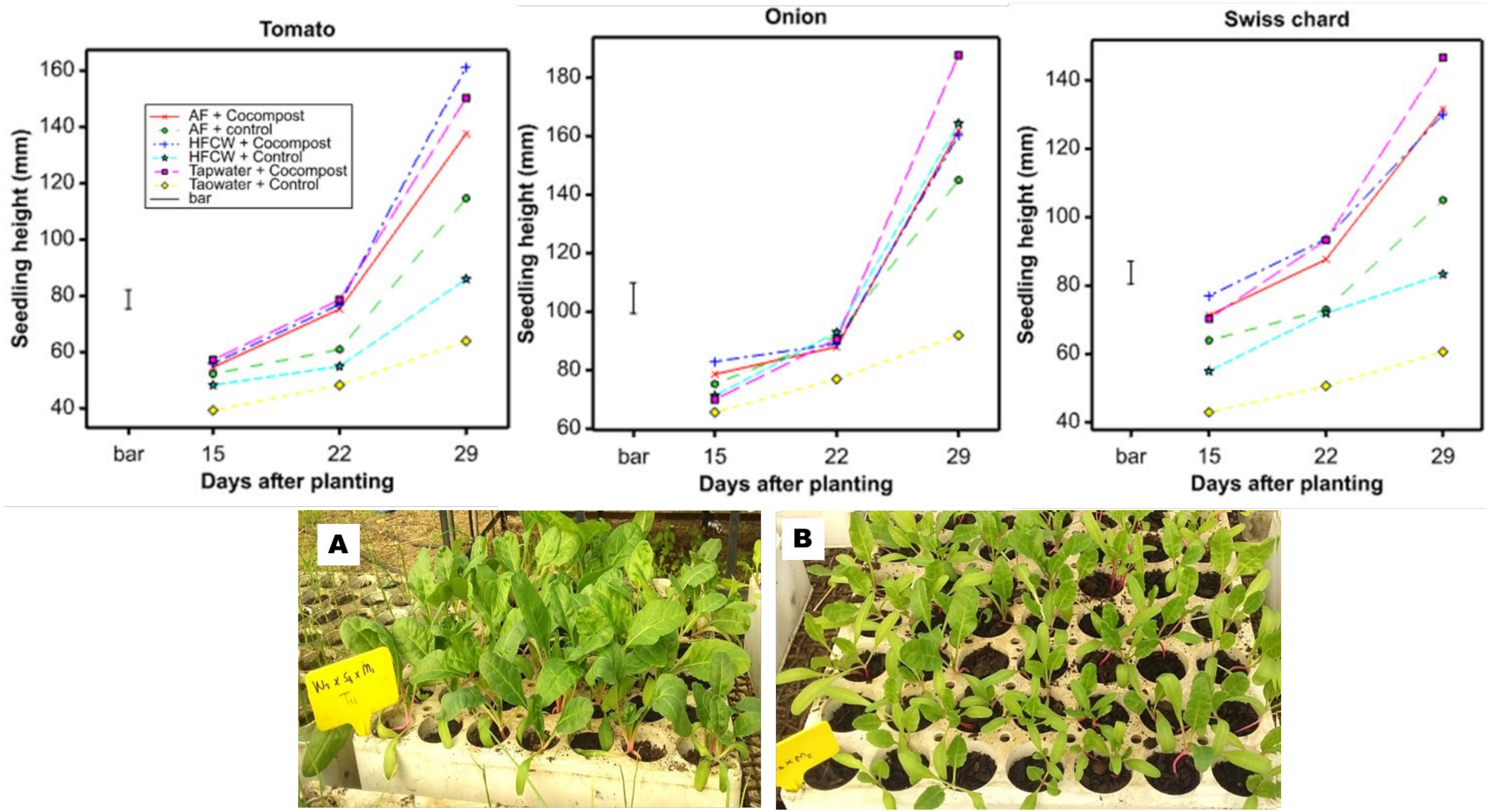

Figure 6.8. Mean values for tomato seedling emergence (%) under various irrigation treatments and growing media for 29 days (n=3, bar is the pooled standard error at 5% significance level). The differences in Swiss chard seedling height between co-compost (A) and control (B).

Seedling dry biomass significantly differed between the co-compost and control media with P<0.05 (Figure 6.9). Higher biomass in co-compost corroborates results reported for seedling height in Figure 6.8. This confirms the argument that co-compost played a role in seedling growth. Even literature has reported increased seedling vigour when faecal sludge derived co-compost is used as a growing media (De Falco et al., 2021; Diaz-Perez et al., 2008; Nartey et al., 2017). The authors attributed these results to increased nutrients from the co-compost. The use of co-compost by small scale farmers for vegetable seedling production provide them an opportunity to obtain high quality planting material that can establish faster in the field.

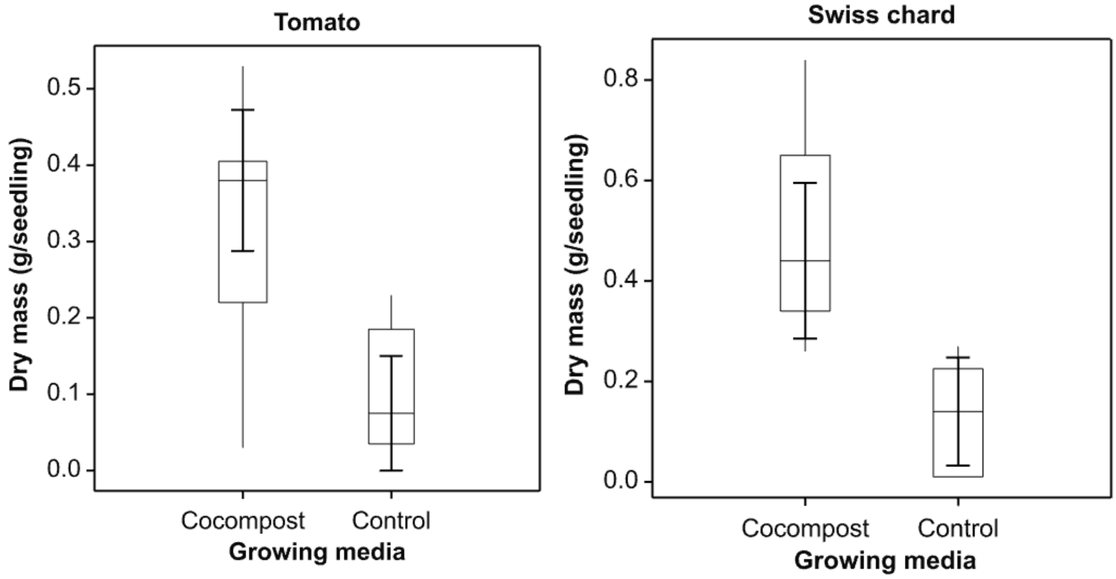

Figure 6.9. Boxplots showing median values and non-parametric standard error for medians for seedling dry biomass in two crops between and different growing media (n=6).

Chlorophyll content is the one of indicators of nitrogen sufficiency in crops (Kalra, 1997). It is also an important physiological indication that has been used to assess water stress in crops. In this study the chlorophyll content was measured in Swiss chard and tomato seedlings due to the nature of their leaves and results are shown in Figure 6.10. Irrigation with AF effluent increased chlorophyll content. This could be attributed to high nutrient content especially total nitrogen. It should be considered that the AF effluent contains some other macronutrients (e.g. Mg and Fe) which are integral components of chlorophyll compounds. The previous section discussed that co-compost played a role on the seedling growth due to high nutrient content and this can be confirmed by high chlorophyll content in tomato seedlings (Figure 6.10).

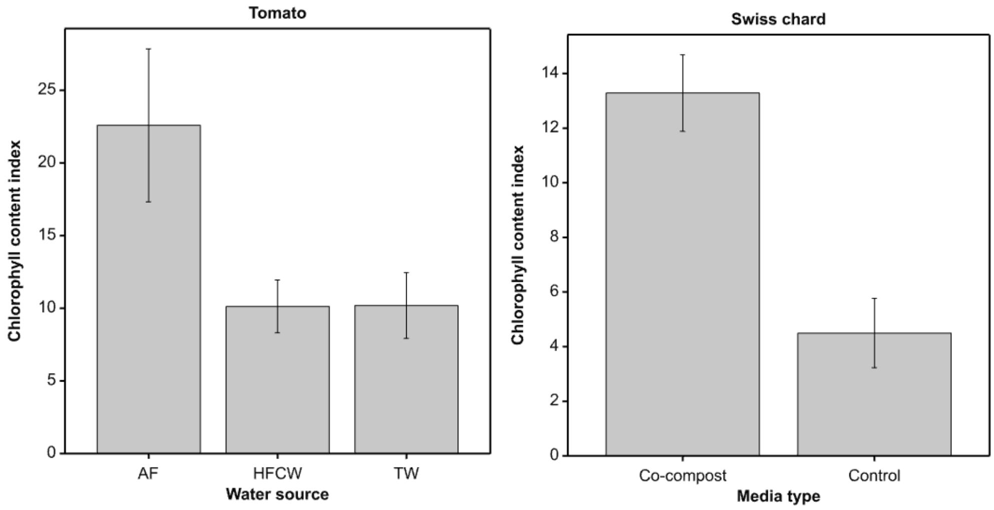

Figure 6.10. The chlorophyll content index (n=3; mean values and standard error of deviations) for Swiss chard in three irrigation treatments and tomatoes in two growing media.

Figure 6.11 shows the final seedling emergence (%) of the various crops in two different growing media. The South African South African Fertiliser, Farm Feeds and Remedies Act of 1947 requires the co-compost for use as growing media to at least meat 80% seedling germination (DALRRD, 2017). All the crops grown in co-compost had mean germination percentages lower than 80% but above 60% except for Swiss chard seedlings. Swiss chard seedling emergence was significantly lower ($P<0.05$) in co-compost compared to the control. Luo et al. (2018) argued that the phytotoxicity of compost depends on species. Some species are sensitive while other are not. In this case co-compost cannot be deemed phytotoxicity with regards to results obtained in Swiss chard (63.8%) because similar results (<80%) are also shown in the control (Onion = 74% and Tomato = 68%) see Figure 6.11. These observations corroborates findings by Nartey et al. (2017) who reported an emergence percentage of 68% in tomato germinated using 50% faecal sludge co-compost. According to Ravindran et al. (2016) composts that support seedling emergence up to 50% are considered ideal for agricultural use. This apply to the studied co-compost which met this criterion.

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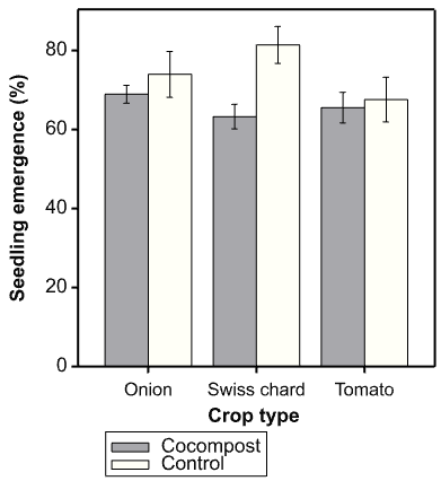

Figure 6.11. Seedling emergence (mean values and standard error of deviation) for all crops growing in two different types of growing medias after 15 days of the experimental period.

6.3.3.2 The characteristics of growing media and seedlings

The major concern when using co-compost as a seedling growing media is the presence of plant pathogens. Seedlings are delicate and require intensive care such that the Seedlings Growers Association of South Africa (SGASA) have stipulated quality standards for certification of seedling production nurseries. The growing media must be free from pathogens such as Phytophthora, Pythium and Rhizoctonia. The same applies to international standards where root disease free growing media is important (Miller and Jones, 1995). In this study the results on the presence of root diseases in the growing media are shown in Figure 6.12. All the growing media were free from *Phytophthora* and *Rhizoctonia.* Only *Pythium* species were detected in one third of the tested conventional growing media and all the tested co-compost samples. Two species (*Pythium aphanidermatum* and *Phytopythium mercurial*) were found in one third of the conventional media while the co-compost consisted of the *Phytopythium mercurial* only*.* The SAGSA requires total absence of fungal diseases in an ideal growing media. Therefore, both the co-compost and control media failed to meet the criteria. Co-composting is a process that should sterilise the growing media killing all the fungal spores (Hoitink and Poole, 1980). The co-composting was done for over 5 months maintaining temperatures above 50^{o}C. Meaning that the presence of these pathogens could have been introduced through other ways such as poor post composting handling. Integrated diseases management are required to prevent *Phytopythium mercurial spp.* in co-compost. A review done by Lamichhane et al. (2017) showed that managing damping off from seedlings is an emerging area that is complicated and suggested for integrated approaches inclusive of cultural practices and biological methods. According to Miller and Jones (1995) one of the cultural practices is the storage of co-compost on a clean and dry area to prevent contamination*.* Deactivating *Phytopythium mercurial* using fungicidal treatments may have environmental implications as emphasised in literature and has been condemned as the agriculture is transitioning to minimal use of chemicals (Hassanisaadi et al., 2021; Lamichhane et al., 2017). Hassanisaadi et al. (2021) suggested that biological treatment using *Streptomyces spp* in addition to co-composting should be put into lens in the future since this is not yet practical. Therefore, the management of damping off in co-compost should be included in the best practices just like other conventional composts.

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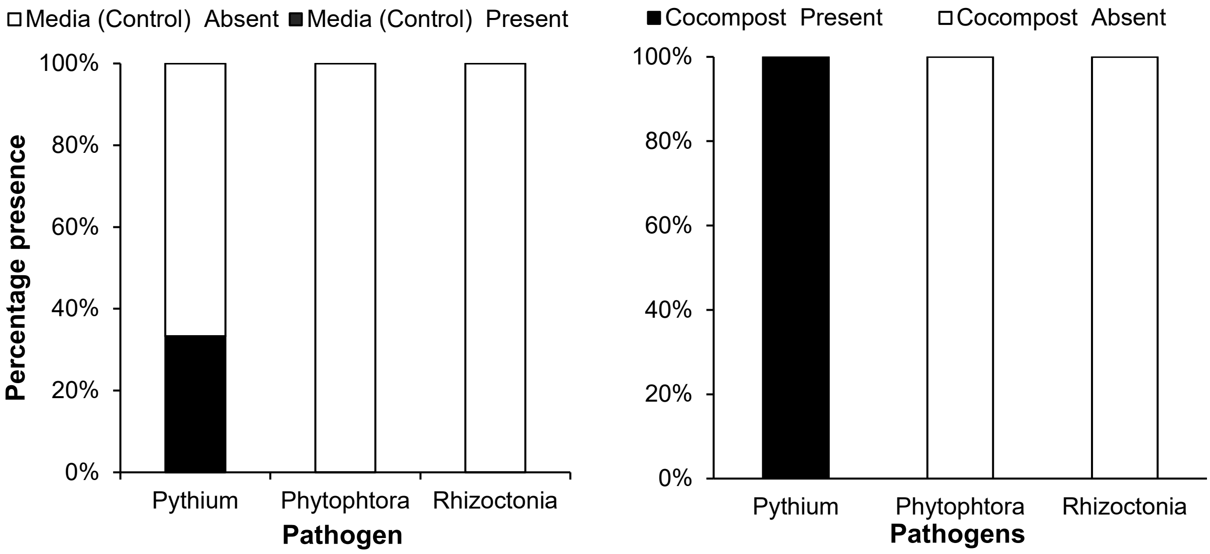

Figure 6.12. Proportional graphs showing the presence of three root diseases in tested growing media that was used for seedlings production (n=3).

The effects of irrigating using DEWATS effluent on root rot pathogens is shown in Table 6.11. There were no significant differences in pathogens detected on plants samples from all three irrigation water sources. *Fusarium spp.* were the only species detected in 33% of all irrigation water samples. A review by Hong and Moorman (2005) showed that treated domestic water harbours myriad bacterial and fungal plant pathogens including the detected *Fusarium spp.* In this case the identified fungal specie could not be attributed to wastewater irrigation as this was also detected in tap water irrigated samples. The *Pythium spp.* were totally absent in all tested seedlings (Table 6.11) than those found in the co-compost samples (Figure 6.12.). This further support the earlier argument that the *Pythium spp.* was not related to co-compost but accidental contamination during handling. The presence of plant pathogens is also against the SASGA best practices meaning that water treatment is vital before use for seedling production. Entailing that post treatment methods such as ozonation or UV are required to eliminate plant diseases from wastewater just like other conventional water variants as suggested by Pettitt (2016).

Table 6.11. The detection of plant pathogens of significance to seedlings quality in tomato (presence in percentage of tested samples; n=3).

Irrigation water source	Pythium		Phytophthora		Fusarium		Rhizoctonia	
	Present (%)	Absent (%)	Present (%)	Absent (%)	Present (%)	Absent (%)	Present (%)	Absent (%)
AF	0	100	0	100	33	67	0	100
HFCW	0	100	0	100	33	67	0	100
TW	0	100	0	100	33	67	0	100

6.3.3.3 Effects of DEWATS effluent on seedling potential human health risks

The use of HEDFs should not be hazardous to the workers handling the products at farmer level (see module PSS3 and PCD6 in Figure 4.1). The analyses done on tomato seedlings irrigated using DEWATS effluent showed a zero-pathogen transfer rater of *E. coli* on seedlings (result not shown). This is good according to the South African Occupational Health and Safety Act 85 of 1993 which in this case requires that workers to be protected from health risks. Thus, promoting safe handling of planting materials.

6.3.4 Conclusions

The study investigated the use of DEWATS effluent and sewage sludge co-compost for vegetable seedling production. The use of DEWATS effluent and co-compost increased seedling vigour. Meaning that there is potential for HEDFs to produce healthy and strong seedlings with faster establishment and subsequent economic returns. All the treatments including conventional seedling production practices did not meet the Fertilisers, Farm Feeds, Agricultural remedies and Stock remedies Act no 36 of 1947 requirements for a good growing media in terms of supporting 80% germination except for Swiss chard. However, all the treatments were above the minimum standards (>50%) for an ideal growing media as all supported at least 60% germination implying that the co-compost was not phytotoxic. The same legislation and seedlings production best practices requires the growing media and seedling to be free from root to diseases. *Phytopythium spp.* were found in co-compost and commercial media samples. Poor post co-composting handling have been the major reason for damping off pathogens in the tested samples. *Fusarium spp.* were also found in tomato seedling irrigated with all water sources including the municipal freshwater. Meaning that integrated disease management practices including disinfecting irrigation water prior to use needs to be considered regardless of water source. The use of co-compost and DEWATS effluent complied with the Occupational Health and Safety Act of 1993 that there were no health hazardous traces of *E. coli* on seedlings to expose farmworkers during handling.

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6.3.5 Recommendations

- The HEDFs can be used by small scale farmers to produce their own healthy and strong seedlings that establish very fast in the field, thus, saving input supply costs and contributing to their food systems resilience.
- The presence of damping off pathogens in co-compost growing media and treated wastewater cannot be pinned to the materials as these can also be detected even in commercial conventional materials. Therefore, best practices to treat and prevent post co-composting contaminations are needed and may be difficult to implement by small scale farmers. This may limit commercial seedling production by small scale entrepreneurs as they hardly meet minimum seedling certification standards. They can produce for local markets within their networks.

- With proper guidance from private sector, the SGASA and the certification boards and DALRRD extension there is potential to support communal entrepreneurs produce high quality seedling using HEDFs.

6.4 Appelsbosch case study

6.4.1 Introduction

Production of high value crops such as tomatoes brings high financial returns per unit area in land scarce areas such as informal settlements. Horticulture improves livelihoods for low-income communities. Urban agriculture is prominent in countries such as Ghana where farmers are producing vegetables using wastewater for the Accra market. About 90% of the total vegetable supply in Accra comes from local urban production (Amoah et al., 2017). Urban agriculture can be limited by space and land which makes intensive greenhouse production an option. As mentioned in the previous section market availability for co-compost is a challenge (Section 5.1). Utilisation of co-compost as a growing media for seedling production has been explored with promising results (Section 6.3). There is an opportunity to use co-compost as growing media in greenhouse production.

Apart from market constraints, postharvest losses are major threats to small scale agriculture. To improve food systems resilience, the project greater vision was to establish an agro-processing hub that will operate at commercial scale and feed into the food supply chain. The challenge was that the BALL does not have enough area and capacity of farmers to produce enough feedstock for agro-processing. In this regard several farmers and farmlands were being explored within the KZNCC networks. This section reports a case study on experience encountered during engagement with a cooperative from Appelsbosch, implementation of using co-compost for vegetable crop production and lessons learnt.

6.4.2 Approach

A cooperative from Appelsbosch was identified after engagements with KZNCC. The manager was engaged to understand activities on the farm and how the roadway for collaborations can be mapped. The farm was productive and they were growing various vegetable crops. The research team consulted and agreed with the cooperative to support with planting materials, growing media (co-compost) and there were prospects to establish an agro-processing area on the site or produce at scale. The tomatoes were planted using co-compost and some coco peat mix as growing media. The chilles were grown in co-compost potting mix (Figure 6.13). Considering the lessons learnt from community engagement (Section 3.4.2), adaptive approaches were developed and used. The project team used participatory planning and implementation of problem-solving techniques during the project. The cooperatives had strong agricultural experience while the project team had circular bioeconomy expertise so there was exchange of knowledge and ideas.

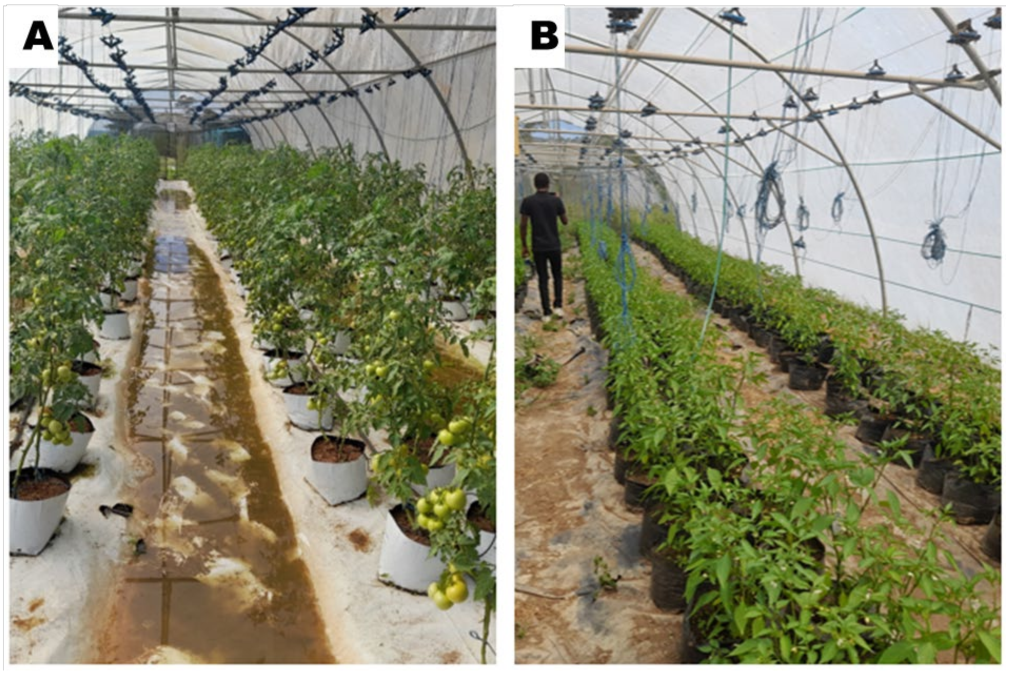

Figure 6.13. The tomatoes (A) and chillies (B) grown in the tunnels at Appelsbosch farm operated by a cooperative.

Monitoring and evaluation was done on the chillies and tomatoes grown by the farmers in their tunnel. Data was collected on yield parameters for the chillies and tomatoes grown using co-compost growing media and compared with other planting media. A systematic sampling method was used to provide a preliminary information on the responses of tomatoes to co-compost vs conventional media. Sampling was done on four inner rows within each greenhouse and every fifth plant was selected for data collection along each row. The number of visible fruits per plant were counted and recorded.

The collected data was subjected to analysis of variance (ANOVA) using GenStat 21th Edition (VNSi Pvt Ltd). The data was analysed at 5% significance level. Where significant differences were noted the Bonferroni multiple comparisons were used to separate differences between means and the data was tabulated and sometimes reported in graphs.

6.4.3 Major findings

Transitioning to a circular bioeconomy requires participatory approaches which include target communities or beneficiaries as drivers of the project. In this juncture, the potential benefits of using co-compost as potting media in tomato production was assessed (Figure 6.14). In agronomic studies tomato yield is determined as number of fruits per plant, plants per unit area and tomato mass per unit area (Dursun et al., 2019). Destructive harvesting could not be done but based on number of fruits observed, very clear yield differences between the two treatments were found. The co-compost produced tomatoes yielded relatively fewer fruits compared to conventional coco peat media although all the fertilisers, irrigation water and management practices were applied equally. These findings are contradictory to results reported by Stiles (2015) who reported better yields in tomatoes

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grown using 45% compost compared to peat moss. Water stress have been assumed as one of the reasons for poor yield. The site faced some power blackouts which interrupted water supply during some periods. Therefore, an assumption was made that the co-compost could not retain moisture content compared to coco peat. The same was raised by another scientist using the same type of co-compost to produce other crops (unpublished source). A study was done to compare the response of producing tomatoes using 30% sewage sludge and 70% co-compost in a semi hydroponic system on yield and quality compared to peat (Aurdal et al., 2022). The tomato yield and quality were comparable since the water supply was not interrupted and nutrient supply was equal.

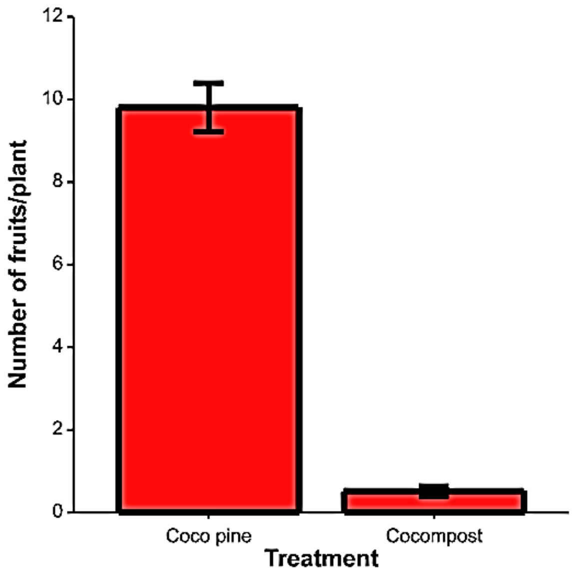

Figure 6.14. Preliminary tomato yield (number of fruits per plant) from the crops grown using co-compost under farmer managed conditions.

The crops grown using co-compost performed poorly compared to coco peat mix. The reasons were not clearly understood and it was risky to recommend co-compost as a potting mix for crop production. The lessons learnt were used to improve and update best practices for agricultural use of HEDFs. This formed the basis for the preceding study.

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6.4.4 The use of co-compost as a growing media for crop production.

6.4.4.1 Background

Sustainable agricultural use of co-compost promotes upcycling of organic materials that are problematic to the environment. Previous section reported the utilisation of co-compost as a growing media for horticultural crops. Poor results were reported in both chillies and tomato crops. The current study aims to assess the phytotoxicity of co-compost using a different crop specie. The fertiliser value of co-compost and its ability to improve soils properties such as nutrient use efficiency were further investigated.

6.4.4.2 Experimental design, layout and establishment

A factorial experiment was laid out in a Completely Randomized Design (CRD). The factors were two soil types (clay vs sand) x four fertiliser types and four replicates giving a total of 32 experimental units. The treatments were co-compost alone (Co), Chemical fertilizer (F), Co-compost + chemical fertilizer (Co + F) and the control in which no fertiliser was applied. The co-compost used in this experiment was made from 25% dewatered sewage sludge and 75% organic green waste.

Soils used during the study were collected from KwaDinabakubo (29°43'59.8"S 30°51'30.7"E) and Bishopstowe (29°35'11.4"S 30°28'44.6"E). The soils were analysed for chemical properties before planting. Soil samples were collected from five different spots on the collection area down to 300 mm depth. The soils were bulked to form three composite samples that were labelled and submitted to FAS for the chemical analyses as in Section 6.2.2.2.2. The maize fertiliser application recommendations were requested. The physicochemical properties of the soils used during the study are shown in Table 6.12.

Table 6.12. Physical and chemical properties of the two soils (KwaDinabakubo; Cartref and Bishopstowe; Clay soils) used during the pot study.

Property	KwaDinabakubo (Cartref soil)	Bishopstowe soil
Clay (%)	12	51.3
Silt (%)	15	16.3
Sand (%)	73	32.4
Textural class	Sandy loam	Clay
Bulk density (kg m^{-3})	1.4	1.1
Field capacity (m^{3} m^{-3})	0.24	0.36
Permanent wilting point (m^{3} m^{-3})	0.12	0.21
Organic C (%)	1.5	2.5
N (%)	0.07	0.19
P (mg kg^{-1})	3	25
K (Cmol$_c$ kg^{-1})	38	487
Ca (Cmol$_c$ kg^{-1})	535	1712
Mg (Cmol$_c$ kg^{-1})	193	435
Exchangeable acidity (Cmol$_c$ kg^{-1})	0	0
Total cation (Cmol$_c$ kg^{-1})	5	13
Acid saturation (%)	4	1
pH (KCl)	4	5
Zn (mg kg^{-1})	1	18
Mn (mg kg^{-1})	3	17
Cu (mg kg^{-1})	2	7

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Collected bulk soils were air dried and sieved through a 2 mm sieve at the Controlled Environment Facility (CEF) of the University of KwaZulu-Natal Plant Sciences. The soils were potted in 20 kg pots on mass basis (Figure 6.15D). Inorganic fertilisers were applied at full recommended rates based on the nutrient analysis results from the FAS. The Lime Ammonium Nitrate (LAN) fertiliser was applied at a rate of 80 kg N ha^{-1} at planting. The other 120 kg N ha^{-1} was applied six weeks after planting. In co-compost + fertiliser treatment N was applied to meet the maize requirements at proportion of 50% recommended co-compost to 50% inorganic fertiliser. The 50% recommended rate for co-compost was calculated using the formular in Equation 6.2.

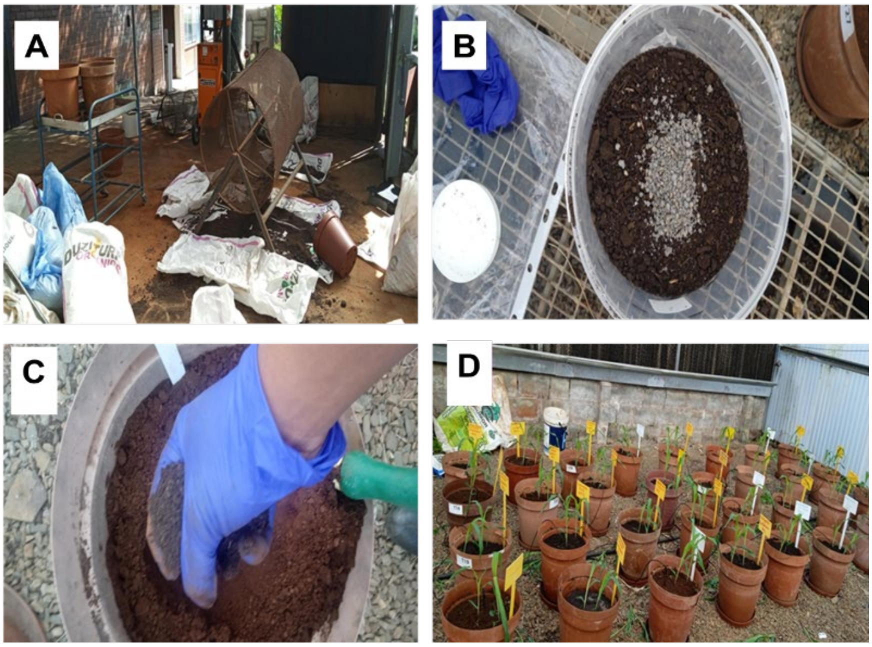

Figure 6.15. Processes for sieving the soil (A), application of fertilizer (B and C) and compost on the soil and maize grown under controlled conditions (D)

White grain maize hybrid seeds (SC 701) were planted at five seeds per each pot to ensure good emergence. Thinning was carried out on the second week after emergence. Drip irrigation discharging 40 mm of water per minute for 10 minutes per day was used to irrigate the trial. The soil moisture was monitored using the Campbell Scientific Model HS2P HydroSense II Handheld soil moisture sensor with Insertion Pole (Figure 6.16) following a maximum soil allowable depletion level of 50%.

Figure 6.16. Measuring soil moisture in maize planted pots using the Hydrosense ™ soil moisture meter.

Plant height was measured from the ground level of the maize plant to the tip of the youngest mature leaf. Chlorophyll content index was measured using the SPAD chlorophyll content meter on a weekly basis. The Easy Leaf Area method was used to determine the total leaf area of maize at six weeks after crop emergence (Figure 6.17) according to the methods by Mandizvo et al. (2022).

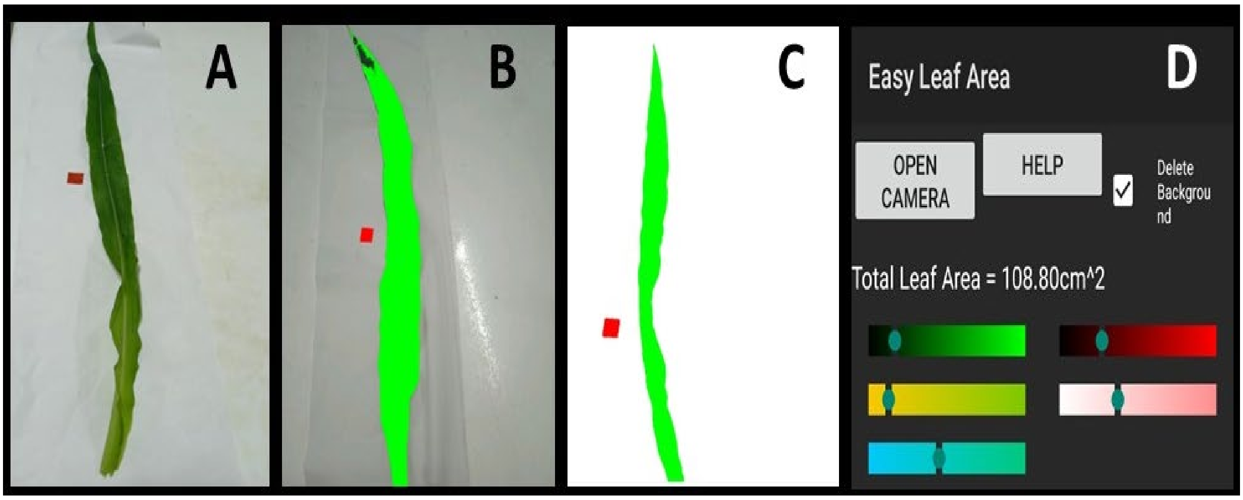

Figure 6.17. Raw and processed photographs of maize (*Zea mays*), unprocessed image (A), images after greenest and red pixel selection (B), image after deletion of the background (C) and total leaf area index (D).

6.4.4.3 Data analysis

The GenStat 20th Edition was used to analyse the data. The quantitative data was subjected to the repeated measures analysis of variance (ANOVA) at 5% significance level. Where $p<0.05$ the Bonferroni contrasts and multiple comparison tests were done to compare differences amongst the treatments.

6.4.4.4 Results and discussion

Crop physiological responses in response to treatments applied were analysed and the growth rate parameters (leaf number, plant height and chlorophyll content index) are shown in Figure 6.18. Crop growth rate significantly differed ($P<0.05$) amongst all the treatments.

Chlorophyll is one of the indicators of nutrient sufficiency and water stress. The responses of plants to deficiencies of nutrients such as N and Fe include chlorosis or yellowing of leaves. The same applies when the crop is water stressed. However, water was applied to meet crop requirements, so it was not a limiting factor. Furthermore, plants with higher chlorophyll content have higher photosynthetic capacity leading to increased dry matter production. Therefore, chlorophyll content measurement using the SPAD is a non-destructive way of assessing crop growth rate in response to water and fertiliser application (Xiong et al., 2015). The maize chlorophyll content in sand soil treatment was significantly lower than all the treatments across the whole study period. The response of maize to nitrogen was evidenced by chlorophyll content pattern in the sand soil + fertiliser vs sand soil + co-compost. The sand soil + fertiliser had relatively lower chlorophyll content during the first five weeks but the pattern changed from six weeks after crop emergence until the eleventh week. The best crop performances are achieved when the co-compost is applied together with inorganic fertilisers to soils. The sand soil + co-compost + fertiliser, clay soil + co-compost +

fertiliser and co-compost alone had highest chlorophyll content values. This could be attributed to the effects of co-compost as a soil conditioner in which the organic carbon increase surface area for N retention. This minimises nutrient leaching and increase their availability for uptake by crops. Efficient fertiliser use in co-compost amended soils was reported by Khatun et al. (2020).

Changes in maize crop height with time is shown in Figure 6.18. Crop height is not only an indicator of growth rate but also a measure of physiological competitive of a crop (Wang et al., 2018). The taller the crop the more exposed it is to resources such as solar radiation and other factors required for biomass production. According to Kirkham (2023) taller plants have a better advantage of exchanging energy with the ambient air. The crop height increases as the growing period progress and reach the maximum before transitioning from vegetative to reproductive phase (Jovanovic et al., 2000). This parameter provides an estimate of biomass accumulated that can potentially be partitioned to harvestable organs. In this study clay soil + co-compost and sand soil treatments had least plant heights across the growing period. The results are consistent with findings reported for chlorophyll content index and leaf number (Figure 6.18), meaning that the less photosynthetically strong the crops the shorter they will be. Fewer leaves and less chlorophyll content directly translate to lesser surface area for trapping radiation, promoting gaseous exchange and synthesising dry matter. Clay soil + fertiliser, clay soil + co-compost + fertiliser, co-compost only and sand soil + co-compost + fertiliser had higher plant heights and leaf numbers. These imply that the use of co-compost can improve the fertiliser use efficiency of poor sand soils. This is crucial to small scale farmers in Sub Sahara region who are battling with poor yields from nutrient mining and degraded soils (Tindwa et al., 2019). Co-compost increased maize growth rate when used as a growing media compared to conventional practices (Figure 6.18), further confirming non phytotoxicity. Increased yields in crops grown using faecal sludge based co-compost was also reported by Fendel et al. (2022) through surveys done on farmers in India. Nartey et al. (2017) showed that the faecal sludge-based co-compost increases tomato growth and yield.

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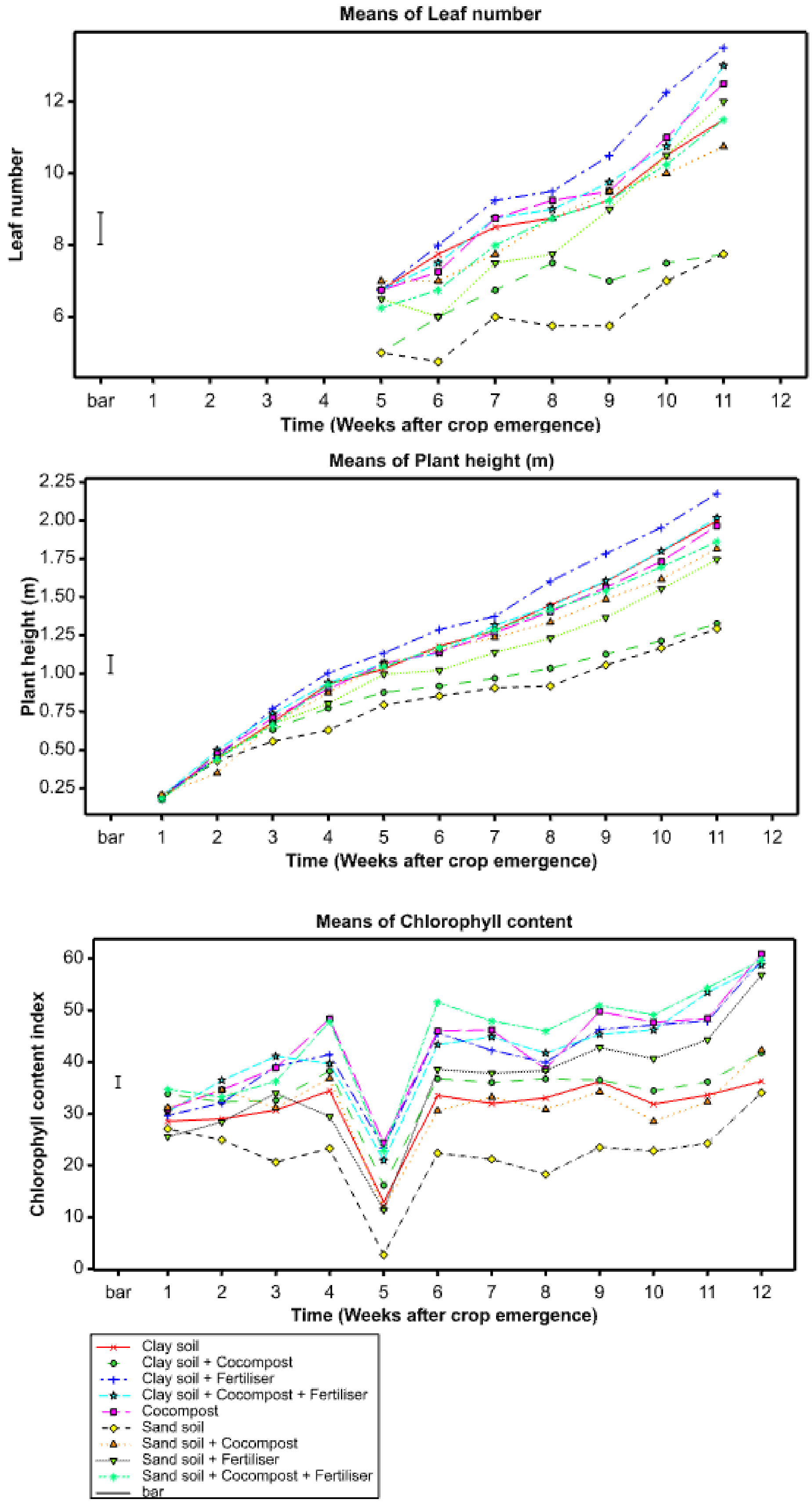

Figure 6.18. Mean values for crop growth rate (plant height, leaf number and chlorophyll content index) in nine treatments (bar represent the pooled standard error f deviation a 5% significance level; n=4).

There were signficant differences (P<0.001) in final total leaf area, root and shoot biomass amongst the nine treatments. Contrasts were done to magnify the differences between the treaments (Table 6.13). Contrasts on root dry mass showed that sand soil + fertiliser treatment significantly differed from clay + co-compost and clay soil while the sand soil differed from clay soil. All the three crop growth variables showed signficant differences between sand soil vs co-compost and sand + fertiliser + co-compost vs co-compost. Total leaf area and shoot biomass significantly differed in the following treatments: sand + fertiliser vs sand + fertiliser + co-compost, sand soil vs co-compost, clay vs co-compost and clay + fertiliser vs co-compost. The sand + fertiliser vs sand + co-compost, sand + fertiliser vs co-compost and clay + fertiliser + co-compost vs co-compost signficantly differed in total leaf area. The contrast done on shoot mass alone showed significant differences between sand vs clay + fertiliser + co-compost, sand + co-compost vs co-compost and clay + co-compost vs co-compost.

Table 6.13. Bonferroni test results showing treatment contrasts (95% significance level) for maize leaf area, shoot and root biomass.

Root dry mass	Total leaf area	Shoot biomass
Sand + Fertiliser **vs** Clay + Co-compost	Sand + Fertiliser **vs** Sand + Fertiliser + Co-compost	Sand **vs** Clay + Fertiliser + Co-compost
Sand + Fertiliser **vs** Clay	Sand + Fertiliser **vs** Sand + Co-compost	Sand **vs** Co-compost
Sand + Fertiliser **vs** Co-compost	Sand + Fertiliser **vs** Co-compost	Sand + Fertiliser **vs** Co-compost
Sand **vs** Clay	Sand **vs** Co-compost	Sand + Co-compost **vs** Co-compost
Sand **vs** Co-compost	Clay **vs** Co-compost	Clay + Co-compost **vs** Co-compost
Sand + Fertiliser + Co-compost **vs** Co-compost	Clay + Fertiliser + Co-compost **vs** Co-compost	Sand + Fertiliser + Co-compost **vs** Co-compost
	Clay + Fertiliser **vs** Co-compost	Clay **vs** Co-compost
		Clay + Fertiliser **vs** Co-compost

The Bonferroni multiple comparisons tests were done on shoot and root biomass and total leaf area (Table 6.14). The sand soil and sand + fertiliser treatments had the least shoot biomass compared to other treatments. The highest shoot biomass was observed in the co-compost media. The results are consistent with chlorophyll content, leaf number and plant height reported in Figure 6.18. On a physiological point of view chlorophyll content and leaf number increase photosynthetic capacity of a crop and subsequent dry mass production. Root biomass and total leaf area play a role in dry mass production where by the denser the roots the more water and nutrients are taken while the higher the total leaf area the more surface area available for radiation use efficiency (Jovanovic et al., 2000). This explains why the shoot and root dry mass and total leaf area were relatively high in co-compost media. The results further confirm the ability of co-compost to retain nutrients such as P in the soils. Higher root biomass and total leaf area were observed in sand soil + co-compost compared to sand soil + inorganic fertiliser.

Sandy soils are highly drained so they can lose nutrients during irrigation events and this could have been stopped or delayed by organic compounds from co-compost which increase surface area for nutrient adsorption and exchange with the soil medium. This corroborates findings by Głąb et al.

(2018) who reported that sand soil amended with sewage sludge co-compost increased crop growth compared to maize straw co-compost.

Table 6.14. Bonferroni test results showing treatment mean differences for maize leaf area, shoot and root biomass (n=4).

Treatment	Shoot biomass	Root biomass	Total leaf area
Sand soil	1.24^{a}	0.30^{ab}	78^{ab}
Sand soil + Fertiliser	1.90^{ab}	0.27^{a}	64^{a}
Sand soil + Co-compost	4.28^{ab}	0.84^{abcd}	202^{bc}
Sand soil + Co-compost + Fertiliser	4.77^{ab}	0.70^{abc}	201^{bc}
Clay soil	5.10^{ab}	1.27^{cd}	128^{ab}
Clay soil + Fertiliser	5.70^{bc}	0.89^{abcd}	174^{ab}
Clay soil + Co-compost	4.69^{ab}	0.96^{bcd}	190^{abc}
Clay soil + Fertiliser + Co-compost	5.23^{ab}	0.81^{abcd}	179^{ab}
Co-compost	9.85^{c}	1.43^{d}	317^{c}

Superscript a, b, c and denote means which as significantly different in each column

A study with farmers in Appelsbosch showed that co-compost could not support either chilli or tomato production. However, further studies using maize showed that the co-compost could not damage the crop but increased its physiological performance. After consultation with the farmers it was learnt that they faced severe pests and disease outbreaks which damaged their crops. This could have contributed to poor fruiting. The fertiliser was applied at recommended rates following the fertigation program. The situation was exacerbated by lack of labour during critical periods, e.g. weeding and harvesting.

On a sustainability point of view, Rezaie et al. (2022) suggested that successful implementation and adoption of circular economy practices should address several challenges faced by farmers. These approaches include providing training on good agricultural practices (sustainable crop protection practices, fertiliser management, irrigation management, etc.). Okem and Odindo (2020) suggested that indigenous knowledge needs to be incorporated in educating farmers on best agricultural practices. In this situation farmers seemed to be well knowledgeable of their cropping practices (Section 3.3.2.2) because the farm manager was accredited with Agricultural Sector Education Training Authority (AGRISETA).

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The major challenge was financial capacity to support intensive agriculture which needed adequate labour and agrochemicals. Through discussions between the project team and the farmers some of the options was leveraging funding to support their agriculture. For example, contract farming with potato chips company was put into lens since the 10 ha of the land required was available. The farmers did not comply with microfinancing requirements; they did not even have a business account and they were not registered the with South African Revenue Services. It was learnt that farmers should be educated about compliance in agribusiness (Section 3.4.2). The project timeframe and resources impeded the project team from directly assisting them, however, efforts were being made to apply for some funding. Considering the complexity of addressing challenges faced by farmers in a real life situation, it is imperative that pilot studies should be implemented to support adoption and utilisation of circular bioeconomy products as recommended by IWMI (2016).

On a policy point of view, there must be flexibility in microfinance compliance policies to accommodate small scale farmers as part of just transition. However, this is possible if adequate evidence-based information is provided. According to Otoo et al. (2018) private sector companies are profit orientated they are involved where loss risks are low. Meaning that private microfinances may play a role if the concept of resource recovery and reuse of agriculture is practically proven.

6.4.5 Conclusions and recommendations

6.4.5.1 Conclusions

The study tested the phytotoxicity of co-compost with a presumption that it could not support chilli and tomato production. Results obtained proved that the co-compost has no negative effects on crop growth and physiology when used as a growing media. Further to that its ability to improve soil properties and fertiliser use efficiency was shown in a poor sandy soil. Consultation with the farmers showed that they are facing problems in purchasing agrochemicals as evidenced by a severe pest and diseases attack that destroyed the crops. The farmers do not have adequate funding to pay for expenses such as labour and agrochemicals. The challenge is worsened by lack of compliance to access loans. Therefore, more education and guidance on agribusiness management is required.

6.4.5.2 Recommendations

- Appelsbosch farmers had an advantage of being led by an AGRISETA accredited leader who provided them with proper guidance on best agricultural practices. From this study it can be deduced that extension officers should that will train farmers should be educated about sustainable agriculture principles.
- Co-compost is good soil conditioner that should be used in parallel with inorganic fertilisers.
- The small-scale cooperatives are hardly producing profitably to meet market demands due to lack of human and financial capacity. Farmer training curriculum should include an aspect of compliance in agribusiness management.

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7 SMALL SCALE PROCESSING AND VALUE ADDITION

7.1 Introduction

Although there are established transdisciplinary innovation platforms and approaches to sustainably manage human excreta, the actual use of human excreta derived materials by small scale farmers in almost inexistent in South Africa as is the case in various countries around the world (IWMI, 2016). This is attributed to unclear policies, minimal involvement of private investors due to limited evidence-based information on viable business models and lack of institutional interests by public sectors such as local governments. Some other issues identified in literature include challenges existing on the food value chains; from input supply, agricultural production, post-harvest handling and access to viable markets (Smith et al., 2023). Most CBE studies focused on the input supply side of the value chain, for example fertilisers production, giving little attention to the whole food value chain from production, processing and retailing events. It is important to link the events from HEDFs production to final production for resilient food systems.

Small scale agro-processing can be included as an integral component of a circular bioeconomy. Agro-processing in CBE innovations have been practiced by certain companies. For example, Biocycle ® a South African company worked extensively on research centred around production of secondary products such as bio-oil and animal feed from black soldier fly larva. Integrating agro-processing in small scale agricultural systems requires addressing underpinning issues within the food value chains. There is limited use of HEDFs by small scale farmers who are supposed to be beneficiaries of these interventions. Some of the identified challenges on minimal use of HEDFs is lack of knowledge on their potential benefits on the environment and livelihoods. Some do not have awareness on profitable value chains, markets, and other interventions such as value addition. This report discussed issues around technological capacity (Section 2.5.1, Section 4.3.4 and Section 5.4), best practices for agricultural use of human excreta derived fertilisers (Chapter 6), and social and legal issues (Chapter 3) that need consideration in excreta reuse. With such idea in mind this section assessed the extent to which agro-processing can be incorporated as an integral component of the sanitation value chain by closing a loop across the food value chain while adding value to enhance sustainability of the circular sanitation bioeconomy. The study further proposed value addition options for food crops.

7.2 Approaches to the study

The study used mixed methods to provide a panoramic view of research findings from different perspectives and scientific methods as described by Shorten and Smith (2017). A brief literature review was done and semi structured interviews were used to understand perspectives from key informants. Key informants were experienced farmers and entrepreneurs from agribusiness entities. These included a commercial farmer, a farm manager and a young female entrepreneur in the circular economy field. A Participatory Action Research (PAR) was done to discuss circular economy interventions and facilitate proposition of agro-processing value chains. During the focus group discussion with the farmers, participants were divided into different groups based on age and gender. Visual descriptive tools such as Venn diagrams and rich picture were used to describe facts from proceedings. Presentations were done to all the participants and opinions from each group were discussed to clarify and understand outcomes from brainstorming sessions. One of the non team member guests from the University of KwaZulu-Natal transcribed the proceedings of the Focus Group Discussion (FGD) to minimise bias and provide neutral views. The information was collated and qualitatively presented in the form of resynthesized Venn diagrams and tables.

7.3 South African agro-processing context: Literature review

Post harvest handling involves a series of events from the time a crop is harvested until it reaches the consumer (Fontenot et al., 2023). Agro-processing is part of post-harvest handling which encompasses transformation and value addition of agricultural products. The DALRRD (2022b) classifies agro-processing as part of the manufacturing sector according to the Standard Industrial Classification (SIC). The major benefits of agro-processing include increased handling of bulk agricultural products, increased shelf life and improved business competitiveness (DALRRD, 2022b). With such in mind it can be included as an integral intervention to improve the sustainability of the food value chain involving the use of HEDFs. The use of HEDFs have social, environmental, economic and legal implications, which make compliance an important aspect.

7.3.1 Legal and policy context

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Regulatory compliance and policy support are two major factors in the transition towards a circular bioeconomy. These should be considered across the food and waste value chains, ranging from stockfeed supply to marketing the final product. The South African legal and policy frameworks supporting agro-processing will be identified and discussed in this section.

South Africa have regulations and guidelines to support utilisation of human excreta fertilisers. For example, land application of faecal sludge or sewage sludge derived products is guided by the guideline for utilisation and disposal of sewage sludge: Volume 2 Requirements for agricultural use of wastewater sludge. The guideline provide option for standards and norms that should be followed in accordance with various legislations. Three major governmental departments which play roles in regulating use of human excreta derived materials include the DALRRD, DFFE, DWS and DOH (Snyman et al., 2006). On the agricultural production level, the utilisation of sludge-based fertilisers such as co-compost is regulated by the Fertilizers, Farm Feeds, Seeds and Remedies Act 36 of 1947 to ensure that it is safe for handling and less likely to spread potential pathogens (DALRRD, 2017). The legislation works inter-alia standards and norms on regulating the requirements of sludge-based fertilisers in terms of heavy metal limits for a pollutant class a, the pathogen (faecal coliforms and helminths) limits for microbial class A and stability class 1 requirements. This legislation has not explicitly mentioned regulations to guide on the use of urine as a fertilizer. Meaning that its use can depend on the regulations guiding other materials such as organic fertilizers including blood, bones and faecal sludge.

The use of treated wastewater for fertigation is guided by the South African Water Quality Guideline (DWS, 1996). The risk based and site specific water quality guideline was then published as decision support tool (DSS) to guide on the use of wastewater (du Plessis et al., 2017). The DSS was then developed in accordance with the National Water Act 36 of 1998.

One of the key outputs of a successful circular bioeconomy is contribution to dealing with societal challenges such as unemployment. Meaning that the innovations and interventions are likely to create employment across the waste and food value chains. It is utmost important to consider the rights of all workers across the value chains and strictly adhered to the law. Workers are exposed to health and safety risks across the value as illustrated in Figure 4.1. The basic South African Basic Conditions of Employment Act 75 of 1997 regulates the right to fair labour practices and making provisions for the basic working conditions. In addition to that, the Occupational Health and Safety Act of 1993 regulates the safety of workers at workplace. This applies to measures that minimise health risks to workers at agricultural production and agro-processing levels. The hygienic practices such as access to clean water, bathing facilities and the use of personal protective clothing must be designed for workers (WHO, 2015). Therefore, if there is provision for the European market a social 146 responsibility certificate is must be acquired (DALRRD, 2012).

Food safety is one of the important issues when human excreta is used for crop production. The South African requires all manufactured food products to comply with the Foodstuffs, Cosmetics and Disinfectants Act of 1972. The Act requires all the ingredients to be labelled and harmful substances to be absent for the safety of consumers (DOH, 2023). The same applies to food products made for international markets such as European Union where the general food law is compulsory. The law on food safety and hygiene includes absence of microorganisms and chemicals, and traceability of the product (Hazard Analysis Critical Control Points; HACCP). On the food safety issue, disposal of packaging materials should be done in an ecofriendly manner. Meaning that the packaging materials should consider the EC

1935/2004 legislation which impose extra costs on non-recyclable materials (Ekaterina, 2016). These laws support best practices to protect the consumers from health risks while minimising pollution.

Legal compliance with the national company registration is important when operating as a cooperate. For example, the company should be registered as per the Companies Act 69 of 1984. The law regulates the registration of companies with South African Revenue Services (SARS). This enables the operator to access loans from microfinances and other governmental support programs such as the RESP (DFFE, 2017). Registered companies have opportunities to contract with some agro-processors and are even allowed to export some value-added products. In this regard the registered company benefits from convenience in operations.

Agro-processing has been given attention by the government. South Africa has policies to support agro-processing have been implemented in a way that promote development in low-income communities. The DALRRD in partnership with the National Market Access of South African Agriculture (NAMC), Centre for Competition, Regulation and Economic Development (CCRED), National Development Plan (NDP) and Bureau For Food And Agricultural Policy (BFAP) developed an agriculture and agro-processing master plan (DALRRD, 2022a). The master plan aims to rebuild and restructure the South African economy from the brink of decimation due to economic recession and the previous Covid 19. The master plan mobilises all transformative tools in transforming agricultural systems and value chains, modernise and enhance competitiveness, enhance access to technologies, broaden participation of small-scale marginalised farmers and promote employment through enhanced agro-processing and value addition. This is an opportunity for agro-processing as an integral component of a circular bioeconomy in South Africa.

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7.3.2 Agro-processing as an integral component of a circular bioeconomy concept

As the population continue to increase, coupled with increased industrialisation and economic development waste generation is increasing. Approximately 10million tonnes of food and food waste are being lost annually across the food value chain (WWF, 2017). On the sanitation perspective, almost 30% of the population is using onsite sanitation systems such as pit latrines which a rarely emptied. All the waste emanating from centralised wastewater treatment plants, connected to almost 60% of the households served by flushing toilets, is piling up in hazardous landfills. The landfill airspace is running out at a fast pace and this is costly to municipalities who must look for alternative spaces. Apart from that, South Africa is battling with socio-economic challenges such as food insecurity, high unemployment and increasing costs of goods and services, which are creating social ills such as substance abuse, crime and school dropouts (Chakona and Shackleton, 2019). Hence, sanitation, food waste and socio-economic problems faced in South Africa needs urgent attention.

Agro-processing is defined as the subset of the manufacturing industry that add value to primary and, intermediate animal and plant-based materials into secondary products (DALRRD, 2022b). Primary agro-processing activities include general grading, curing, pre-packaging, cooling or drying and until the product is stored for the market. The secondary agro-processing involves the total production of crops into new products for example orange juice, chilli sauce, etc. (Sisipo et al., 2021). There are various reasons why agro-processing is important for resilient food systems. Processing agricultural products preserves food during off season, adds value to fetch high prices on the market and allows diversification of enterprises (Sisipo et al., 2021). For example, rather than producing a pineapple fruit for fresh market, the fruits can be processed to juice and the remaining pulp used to make other products. Apart from adding value agro-processing stimulate activities across the value chains and contribute to socio economic development. Some benefits include employment creation, reduction/prevention of food waste, increased food security, all year round availability of nutritious food reserves and national economic development (Chitonge, 2021; Owino and Ambuko, 2021). Agro-processing can be done at different technical scales from simple to complex technologies (Chitonge, 2021). For example, simple traditional technologies such as vegetable solar drying have been in practice in developing countries while some sophisticated technologies such as tannery are also available. Meaning that the concept is applicable to small scale farmers.

Considering the identified impacts on economic development, pollution reduction, food and nutrient security, agro-processing is a potential valuable component of a circular bioeconomy. Integrating agro-processing in a circular bioeconomy model promotes human excreta management by creating a demand for all materials used across the value chain from input supply to the consumer. However, there are major challenges that need to be taken into the lens (Table 7.1).

Table 7.1. Barriers for small scale farmers to penetrate profitable agro-processing industry.

Barrier	Source
• Domination of large agro-processing companies	(SACN, 2015)
• Meeting market quality and quantity requirements	(SACN, 2015)
• Access to finance	(SACN, 2015)
• Production systems constraints	(Halos-Kim, 2013; SACN, 2015)
• Competition with cheaper imported products	(SACN, 2015)
• The cold chain maintenance is needed	(SACN, 2015)
• Inability to meet the market quantities	(Halos-Kim, 2013; SACN, 2015)
• Retailers and agents have strong buying power	(SACN, 2015)
• Lack of appropriate technologies	(Gardas et al., 2017; Halos-Kim, 2013)
• Lack of linkages between processors and farmers	(Gardas et al., 2017)
• Lack of market information	(Halos-Kim, 2013)

7.4 The potential of agro-processing as an integral part of a circular bioeconomy: Stakeholder interview.

7.4.1 Attitudes and perspectives towards utilisation of human excreta

The concept of waste recycling was well explained to the interviewees. There were mixed feelings about the use of HEDFs for food crop production. According to S1 the use of human excreta might be a breakthrough for farmers who are struggling to afford fertilisers citing an example of some Zimbabwean communal farmers. Some of these farmers are resource constrained to afford inorganic fertilisers to apply in their fields. This is a challenge to most farmers in Sub Saharan Africa and this is leading to depletion of their soils (Tindwa et al., 2019). The same challenge was raised by farmers during FGD Table 3.1). Meaning that the use of HEDFs have potential to resolve existing fertiliser cost crisis for low-income farmers. In addition to fertiliser value, S1 appreciated HEDFs recycling have multiplier benefits such as minimising pollutants that are entering the environment.

The S2 was concerned about human excreta recycling citing issues such as taboos and religions. The interviewee provided an example of witchcraft when it comes to handling human excreta. Although S2 was concerned about traditional perception on handling HEDFs, an issue of informing the public that the food products were made using faecal sludge need consideration.

> *"People might show positive attitude towards using human excreta but they might not be willing to use their own waste in fear of being bewitched"*

In general people have no problems in using HEDFs for food crops. This has been validated through empirical studies conducted in the same study area. Wilde et al. (2019) did a study with communities from Msunduzi municipality and found out that people were concerned about treatment and aesthetics when it comes to HEDFs. However, there was a positive attitude when it comes to processed urine products such as NUC which is smell free and sterile. A study done by Gwara et al. (2023) showed that people from Msunduzi area are willing to pay for excreta based fertilisers provided that it is safe as endorsed by regulatory authorities. In this case the HEDF products are less likely to face resistance if well treated, certified and appealing.

7.4.2 Legal compliance and regulations

The current South African legislations are not prohibitive on the use of human excreta. However, a further consultation with stakeholders and experts showed that there is no clear legislation prohibiting the use of human excreta fertilisers. S1 mentioned that there are some farms using untreated excreta for agriculture in USA and was not sure if this was legal.

> *"I travelled there for a month for an exchange visit and whilst I was there I was attached to an organisation that deals with agriculture development and they actually wrote an article about a small farmer who was using human excreta but they were not doing it the way you're doing it where you're making fertilisers, processing it and then giving it back to the farmer. So it was probably direct from. I don't know where their collection points were. …………….. So I would also say in the US it could be not a problem".*

According to S1 the European Union markets are very stringent. The interviewee emphasised on the issue of pesticides and other chemical residues as major concerns. However, although S2 was not sure of any global regulation prohibiting the use of human excreta fertilisers, he mentioned the Global Good Agricultural Practices (GGAPs) as something to be considered. According to Moya et al. (2019a) the GGAP has a clause which prohibits the use of any human excreta-based material. These are issues to be considered at an international policy level, where for example, the European Union is advocating for "*with Europe*" transition to a circular bioeconomy (Hoff et al., 2018). The GGAP safety regulations needs to be revised to specify chemicals of concern rather than specific materials. For example, about 90% of the world wastewater is generated into the environment without treatment (WWAP, 2017), and this is used indirectly in agricultural fields. Implying that the faecal materials are indirectly consumed.

7.4.3 Market availability and accessibility

Market availability and accessibility is an important aspect for a sustainable business. The study revealed that there are local and international markets in which agro-processed products can be sold to. An interview with S2 farm revealed that vegetables such as damaged butternuts and cauliflower are processed rather than being dumped. Some of the processing techniques used include dicing are packaging before selling to local supermarkets. The same was reported by S3, who is packaging and selling crops like grade A cucumbers and tomatoes at local supermarkets. The lower grade crops are sold to spaza shops and communities. An interview with S1 revealed that there are regional markets available vegetable crops. It was mentioned that Malawi imports some of their vegetables from countries such as South Africa. The interviewee mentioned lack of knowledge and infrastructure as some of the constraints hindering them from producing vegetables intensively.

> *"I would say Malawi because I say when I visited Malawi, they were saying most of the vegetables in the supermarket are imported from South Africa….................. she was saying we don't have so many products in the supermarket like you have ….. So it's probably their supply chains or infrastructure or something like that..."*

Markets are also available for processed crops such as beetroot, blueberries, leaf vegetables and chillies in countries such as Germany, DRC and China. S1 mentioned companies which have been exporting chillies to Germany and DRC. The S2 was also exporting vegetables such as Swiss chard to countries such as China. According to S2 the vegetable market demand in China is large such that they sometimes struggle to meet demands. Implying availability of markets at local, regional and international levels. The only challenge in accessing European markets is compliance with the GGAP. According to Moya et al. (2019a) countries such as Kenya do not have regulatory issues hindering the use of HEDFs in food crop production. Recently the Swedish Authority has endorsed the use of urine fertiliser "*Aurin* ®" for food crops (Vuna, 2022). Meaning that not all European countries and African countries are prohibiting the trade of food product made using HEDFs. Therefore, proper market research is needed at both regional and international level as suggested by S1.

> *"It will be a matter of market research of just finding out where they can sell…………..."*

7.4.4 Economies of scale and partnerships with private companies

To operate profitably the farmers should produce at scale which is not easy. One of the strategies suggested by S1 to increase operations to economies of scale is aggregation of farmers into cooperatives. The current identified farmers were operating in small unorganized groups, for example the UB cooperatives consisted of six resource constrained farmers, who were not even able to meet labour demands during peak periods (Section 3.3.2.2). A scoping review done by Bizikova et al. (2020) showed that farmers may benefit from increased yields when working in a cooperative. They argued that this is not automatic to unskilled farmers who are resource constrained and marginalized. The benefits are possible if they are provided with adequate training and support. There are training and supports opportunities available for women and youths which are free of charge. S1 provided an example of training workshops provided by organizations such as Zim Trade (citing a Zimbabwean example). However, in South Africa the Agricultural Development Agency (ADA) and many others such as DALRRD are responsible for training farmers and cooperatives.

Creation of an agro-processing hub where farmers can sell their produce is another way of guaranteeing market availability. There is need for an individual or group of people operating and or owning an agro-processing plant. For example, the interviewed stakeholder S1 owns an agro-processing company which manufacture snacks from crop produce. During the interview it was learnt that they purchase their raw materials from communal farmers and other private producers. They mentioned that small scale farmers might not be sustainable, citing an issue of meeting production demand. An example of a goat supply opportunity was given, whereby about 5 000 goats were needed by a certain customer monthly. The target community could hardly meet 50 goats per week and this forced the investor consider other locations.

> *"Yeah, we have the only time I had when they were failing, when they were facing challenges. It was. It's not really vegetables. It was the goat industry. We there is a customer who needs 5 000 goats every month and then someone reaches out to farmers, a group of farmers. I had a conversation with the farmer who said I thought I had so many goats because I had 80".*

On the same case the project team approach a commercial farmer operating in the area to pilot an agro-processing hub. The idea was to connect the farmer to a network of farmers and in addition they can produce extra to feed into the agro-processing hub. The idea was conceptualised but could not materialise due to budget and project timeframe constraints. The ideas were motivated from a model used by one commercial rural farmer and restaurant owner in Zimbabwe (Ncube, 2022). The KwaTerry traditional restaurant cooks local cuisines using indigenous foods, ranging from local goats, chickens and small grains meals. The entrepreneur has attracted local and international attention with various tourists coming from Europe visiting the place. The entrepreneur has enhanced food value chains for traditional chickens and goats, training other local communities to meet his market demands. The entity serves indirectly as an agro-processing hub.

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Production ethics have also been singled out as challenge when dealing with communities. During an interview with S1 it was learnt that some farmers may not provide best quality for production. This may not because they are not trained or able to do that but lack of ethics. For example, some mix seed with sand or stones to add extra mass. This also happens in cooperatives that co-join their produce for the market where one person may vilify the rest of the group. S1 suggested that proper education on public relations is needed for small scale farmers to understand ethics in business.

On the other hand, there are initiatives to protect farmers from under and delayed payment by private middlemen. During an interview with S1 delayed payment of farmers and exploitation occurs. It was learnt that the middlemen or agents must comply with international ethical laws implemented by Fairtrade. Fair trade is an international brand established to protect the small scale and peasant farmers from social injustice (Jari et al., 2013). These regulations are crucial to smooth transitioning to CBE including agro-processing.

The value addition of vegetable crops seemed to be a common practice done by most farmers. S3 mentioned that they were losing a lot of crops as waste and suggested for processing them into tomato sauce or mix with chillies to produce chilli sauce. The same was proposed by S2 who was more in favour of chilli citing its ability to adapt to harsh conditions and minimal needs for inputs.

Therefore, operation at economies of scale needs aggregation of small scale farmers, awareness and training on business ethics, recognition of Fairtrade policies and understanding and capitalisation of local indigenous systems.

7.5 Community Focus Group Discussions

7.5.1 Vulindlela Case Study

The extent to which farmers understand the concept of agro-processing and value addition was assessed. The farmers showed to have minimal knowledge on agro-processing as evidenced by their inability to define the concept. After the concept was explained farmers were able to provide examples of some value addition practices. The project team explained the concept of small scale and large scale agro-processing, citing various examples such as production of tea from tea leaves, grinding herbs such as moringa and production of tomato paste using tomatoes. This was done to show them that agro-processing is not only about complex practices but can be day to day activities which may include traditional postharvest activities. In agreement with discussions emanating from the previous section (Section 7.4.4), incorporation of indigenous knowledge systems in CBE innovation improves food systems while maintaining traditional integrity. A review by Okem and Odindo (2020) encourage the incorporation of indigenous knowledge in reuse as a sustainable option.

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> *"Agro-processing is a method of producing crops"*
>
> *"Agro-processing is the use of advanced technologies for agriculture"*

The farmers are not able to process their agricultural products. As a result they are losing a lot of produce as food waste. One of the challenges identified during the FGD was the lack of appropriate technology. They are unable to purchase state of art and fit for purpose technologies since they do not have financial capacity to do so. In addition to that they lack knowledge and expertise on operating sophisticated technologies and markets to sell their products. These issues have been mentioned in literature, for example Musyoka et al. (2020) referred to lack of funds, access to cold storage facilities, prices of the value added products, group membership, extension contact, farmers awareness and availability of adequate labour as major hinderances. In such systems small scale farmers are not able to operate profitably. This system has implications on the food value chain. If the farmers are not able to be operate at profitable capacity, they will be not create employment in the communities. It should be noted that agro-processing involves transportation of feedstock, pre-treatment, processing and packaging.

Identified crops that can potentially be processed at small scale included maize, potatoes, carrots, butternuts, and pumpkins and in addition to the list other crops included were cabbage, Swiss chard, sugar beans and green beans (Figure 7.1). Cooperative 1 (C1) identified maize as their main choice crop, which they can sell as green maize or process into roasted maize, maize meal, porridge, stock feed, samp and soups. The same products were mentioned by Pillay et al. (2014) as common products made from maize by various low-income communities of South Africa. In addition to that there is an opportunity of closing a loop for the maize values. For example, samp production generates waste that can be used as chicken feed and this can be beneficial for C1 which is interested producing chickens for egg production.

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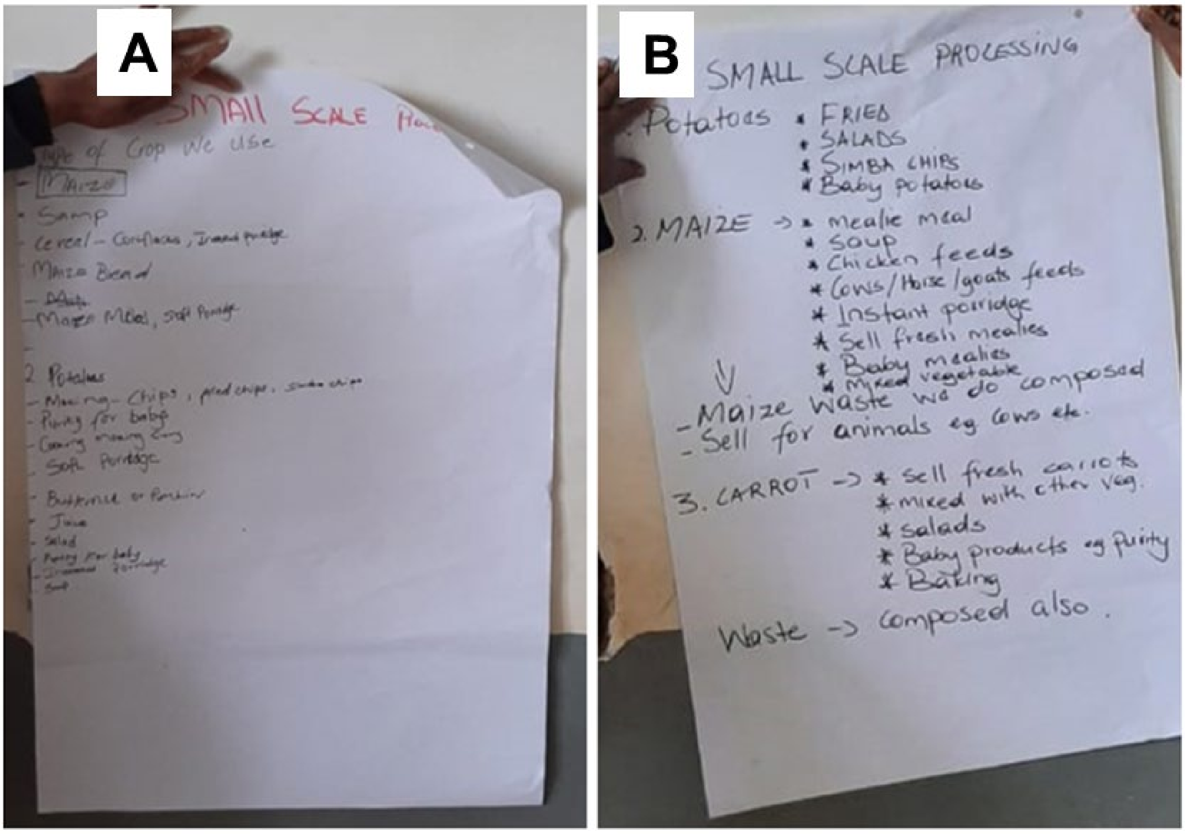

Figure 7.1 Agro-processing opportunities identified by the target farmers (Group A and B).

Dry bean is another crop that the farmers proposed to grow and sell to the nearest hospital. The dry bean may be added value by mixing it with maize samp, packaging and selling. Potato is one of the crops proposed and has been seen in gardens of many farmers. The participants of the FGD proposed that they can grow potato for processing into fresh fried chips (French fries). French fries and meat curry are some of the foods cooked and sold by many restaurants in identified community. The participants had an idea of linking agricultural production with fast foods as a value addition option. Some proposed potato processing included peeling, cutting, packaging and freezing before selling them as frozen potatoes. The carrots were identified as crops that can be grown in rotation with vegetables such as Swiss chard. Farmers identified potential small-scale processing of vegetables such as carrots, baby corn and green beans into mixed vegetables that can be sold frozen.

The processing of maize, potato, carrots and other crops needs investments in machinery, power, labour, land and water supply. Market availability might be an issue of consideration as discussed in Section 7.4.3. In this regard, producing crops for local restaurants will be financially sound and sustainable. There is an opportunity to create a rural resort that can be marketed to the international and local community. That's a way of capitalising on local markets rather than stringent international ones. Linkage with the international market will be indirect through tourism attraction as is the case of “KwaTerry” model (Section 7.4.3). The only linkages they can make within the CBE is production of Black Soldier Fly Larvae or growing yellow maize using co-compost for chicken feed. This is an opportunity for one of the identified cooperatives called “Mfenendala” from Sobantu that is producing traditional chickens for the local market (Section 3.3.2.4). Such initiatives agree with the SDG 11 encouraging co-creation of sustainable cities and communities whereby target 11.4 is centred around strengthening efforts to safeguard the cultural and natural heritage.

The farmers were dedicated and aspired to target large companies through contract farming. They approached a company producing potato chips to gather information on possibility of supplying them with produce. Unfortunately they could not comply with the stipulated minimum requirements. These included having access to adequate land that will support uninterrupted supply and tax compliance. These regulations are established to ensure reliability, transparency and accountability. For example, during an interview with S1 (Section 7.4.3) it was learnt that most small-scale farmers were unethically compromising quality of the product for payment and unable to meet production demands. Besides that the S1 mentioned that it is easy to provide training and finance augmented or organised farmers rather than individuals. In the future, farmers should consider grouping into cooperatives, target production at scale and comply with financial regulations if they are to aim competitive markets.

7.5.2 Sobantu Case Study

Figure 7.2 summarises food value chains proposed by farmers and respective agro-processing options. In this study four crops that were mentioned by all groups were chillies, onion, cabbage and spinach. Groups A and B participants were all interested in carrots and beetroot while the Group A alone had potatoes, maize and beans. The same crops were even proposed by the farmers from Vulindlela during the previous meeting with a women owned cooperative (Section 7.5.1). The production of potato chips, chilli sauce, canned beans, roasted maize, slicing and dicing beetroot and packaging of mixed vegetables have been proposed as well by Vulindlela farmers. Coleslaw and chutney production refer to processing of agricultural products into salads that can be include in most of the South African dishes. This link with the ideology brought up by farmers from Vulindlela that crop production may be linked with local restaurants supply chains. It also interconnects the creation of traditional chicken value chains linking with activities from Mfenendala cooperative.

The production of potatoes to supply private companies might be a challenge and not an option. Potato chips production was once followed up by one of the participants from Vulindlela, who managed to obtain basic information on accessing processing companies.

The company contracts farmers who meet the criteria discussed in Section 7.5.1. Discussion with farmers in Appelsbosch and Vulindlela revealed that most small-scale farmers do not have capacity to access loans and do not comply with the requirements of the potato farming contract. Therefore, this option could not be considered.

Some farmers proposed the onion value chain and provided an option for chopping and packaging it for sale. However, other crops of considerations that were not proposed by farmers are garlic and ginger which can be used to make paste or be dried, ground and packaged. A discussion with S3 from Appelsbosch provided an insight that crops such as garlic, ginger, greenhouse cucumbers and cauliflower are less attractive to theft because they are considered luxurious (Section 3.3.2.2). Thus, further information is needed to understand reasons why the farmers are not considering such options.

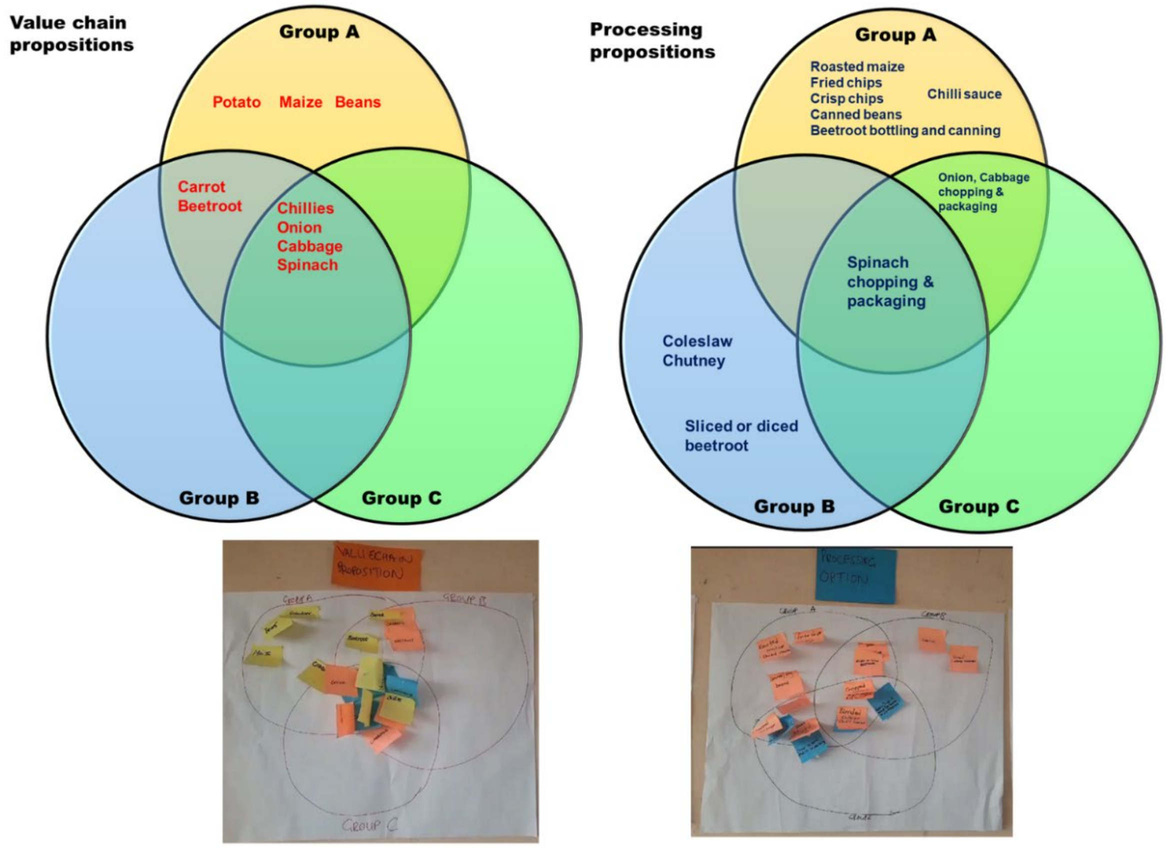

Figure 7.2. Venn diagrams showing the similarities and dissimilarities in ideas on value chains and processing options amongst the three groups (Group A, B and C).

The Strength, Weakness, Opportunities and Threats (SWOT) analysis for the participating farmers is shown in Table 7.2. The farmers have adaptive skills to deal with irrigation, pests and diseases and access to agricultural equipment. The study unveiled that market availability is not a problem because farmers can easily sell to local traders. The major weaknesses are that they don't have state of art agricultural equipment, capacity to employ casual labourers, security and storage facilities. Which is expected in small scale agro-systems (Halos-Kim, 2013). As a result they are unable to produce at scale to meet the markets demand. According to the DALRRD (2022b) the South African small scale agro-processing industry is facing challenges such as inadequate and inconsistent raw materials supply, appropriate technologies and inadequate on farm infrastructure. This makes the inclusion of agro-processing in circular economy difficult unless the farmers are organised, well equipped, and funded to operate at scale and meet expected standards (Bizikova et al., 2020; Piñeiro et al., 2020). The production at scale gives farmers a competitive advantage at the market. Furthermore, lack of storage facilities implies that postharvest losses will be expected if agro-processing is not done. Thus, justifying the importance of agro-processing as a valuable component to maximise profits, minimise generation of waste and increase food systems resilience (Sisipo et al., 2021).

Table 7.2. The farmer situational analysis using the strength, weakness, opportunities, and threats (SWOT) approach to assess their potential capacity to establish profitable circular economy business models.

Strengths	Weaknesses
• Use of adaptive methods to address irrigation water challenges • Some farmers have marketing stands • Use of available simple agricultural tools • Adaptive methods to get labour from volunteers • Sharing tools • Knowledge on cultural pest and disease control methods	• Lack of capital to purchase irrigation and agro-processing equipment • Lack of state of art agricultural tools • Lack of capacity to pay for labour • No knowledge on soil testing • Lack of storage • No security for theft
Opportunities	**Threats**
• Demand for agricultural products from informal traders and households • Input supply programs from DALRRD	• Competition for markets with commercial farmers 158

7.5.3 Participatory stakeholder mapping

The identification of stakeholders that are crucial to implementation of agro-processing intervention in crops produced using HEDFs is shown in (Table 7.3). The study took a value chain approach to map stakeholders that are crucial to safe, productive and efficient agricultural production of best processing crops of high value products that attract lucrative markets. Based on recommendation by Halos-Kim (2013) a multistakeholder interaction between the research and development institutions, agricultural and industrial sectors is needed to achieve this. Research, innovation and farmer organisation also play a pivotal role meaning that an agro-processing hub owned probably by a well-established private owner may help link small, fragmented farmers to one market.

The DALRRD is mandated to foster food security to households by providing farming solutions through extension services and input supply. Governmental interventions are not new but common as reported in other countries and their impacts on national food security were reported (Denning et al., 2009). Co-compost production is a less profitable business entity with returns on investments of 8 years (Nikiema et al., 2020) while struggling with markets due to minimal usage by farmers. The agricultural use of faecal sludge derived co-compost is not well practiced globally. IWMI (2016) suggested that co-compost utilisation can be increased if demands are created by enhancing food value chains from production to marketing. Halos-Kim (2013) mentioned that if preharvest and postharvest management practices are enhanced through technological support farmers are attracted to invest in agribusiness and possibly adopt circular bioeconomy interventions such as the use of co-compost. The DALRRD have farmer incentives programs in the form of extension services and provision of agricultural inputs. Furthermore, the DALRRD have policies to support value addition, e.g. the agriculture and agro-processing master plan (DALRRD, 2022a). This presents an opportunity for them to adopt and disseminate the circular bioeconomy interventions by, for example, creating market chains for producers to sell HEDFs which they may subsidise for farmers.

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Table 7.3. A mapping exercise results on the role of various stakeholders across the food value chain.

Value chain	Stakeholder	Role
Farm production	• Private companies (e.g. seed companies)	• Input supply and contracting, e.g. in seed maize production
	• DALRRD	• Input supply subsidies, extension services and fertiliser registration/certification
	• DWS	• Access to human excreta for co-composting
	• Hardware suppliers	• Innovative equipment
	• NGOs (e.g. AFRA, Gift of the givers)	• AFRA is responsible for advocacy on land tenure in marginal communities. • Gift of the givers has a component of supporting subsistence agriculture through input donations
	• Academic institutions	• Trainings and expertise support on best agricultural practices
Processing	• Research institutions (DSI, CSIR, UKZN)	• Research and innovation on small scale agro-processing technologies to suit small scale farmers
	• Private companies (commercial farmers and processors)	• Private companies may own an agro-processing hub and contract small scale farmers • Commercial farmers may link small scale farmers to agro-processors
	• Duzi Turf	• Safe compost supply for seedling production
	• Land Bank	• Agricultural development funding
Marketing	• Customers	• Marketing resulting products
	• DTI	• International market linkages and compliance for small scale farmers
	• Mkhondeni Fresh Market	• Graded fresh produce market
	• Mini Markets and supermarkets, e.g. Shoprite and boxer	• Marketing of processed products

After having identified stakeholders required for agro-processing in CBE models, their interactions are summarised Figure 7.3. The research institution moderates all the activities by providing research to address challenges emanating from all activities. In collaboration with other research financing institutions they can develop state of art and better technologies to support smooth operations and build capacity by coordinating trainings.

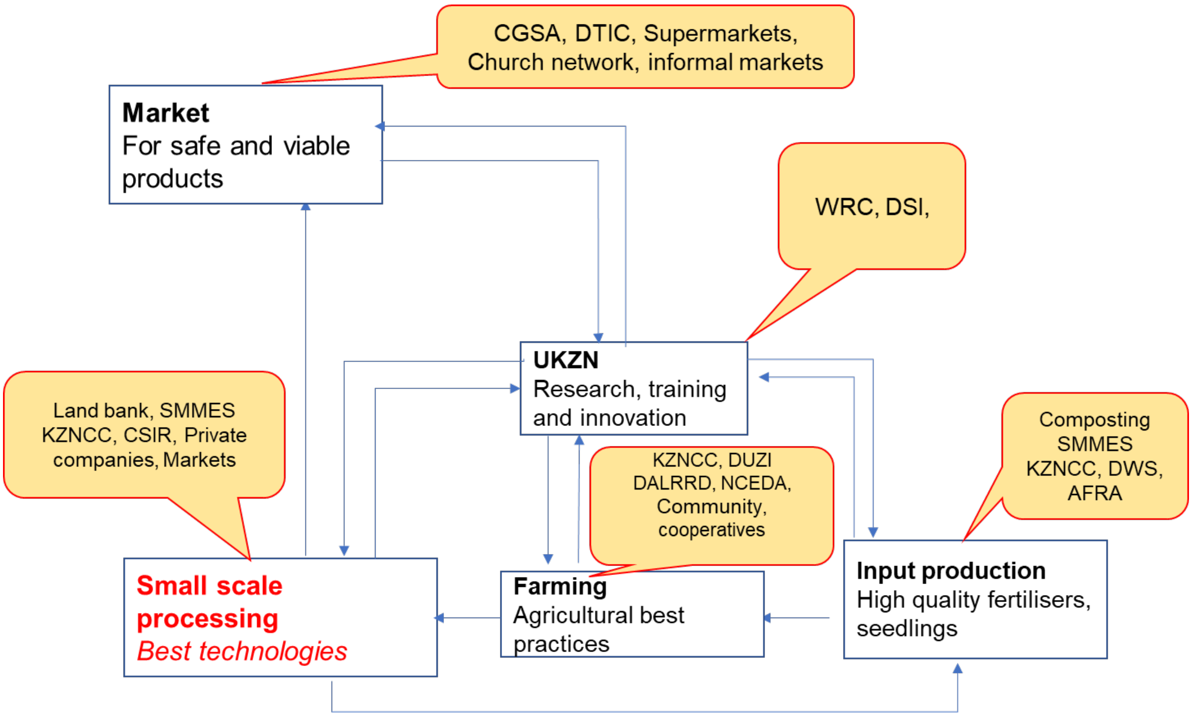

Figure 7.3. Summarised interactions of stakeholders (shown by arrows in a feedback mechanism kind of activity) in an agro-processing value chain innovation moderated by the academic institution (UKZN).

7.6 Quality control and compliance: Post-harvest handling and processing of chillies case study

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7.6.1 Introduction

Value addition and agro-processing play a pivotal role in maintaining the quality of the agricultural product, ensure food security and promote diversity of income streams. There are various technologies available for agro-processing ranging from natural methods such sun drying to sophisticated machinery. Technological requirements in a circular bioeconomy were discussed in Table 2.3 of Section 2.4. The key aspects include research and innovation to identify, improve and design energy efficient technologies, assess feasibility of selected technologies for commercial application and recommend innovative approaches for integrating the principles into value chains . Chilli pepper value chain was selected for a case study after a series of consultations with stakeholders and farmers (Figure 7.4). This section reports on optimising the chilli processing through research and innovation in a circular bioeconomy. The study investigated (i) effects of pretreatment such as blanching on nutritional quality of chillies grown using HEDFs, (ii) optimise the chilli drying process using different approaches and (ii) their pathogen contamination levels for human consumption safety in accordance with hypothesis PF2 – PF4 of the Figure 4.1.

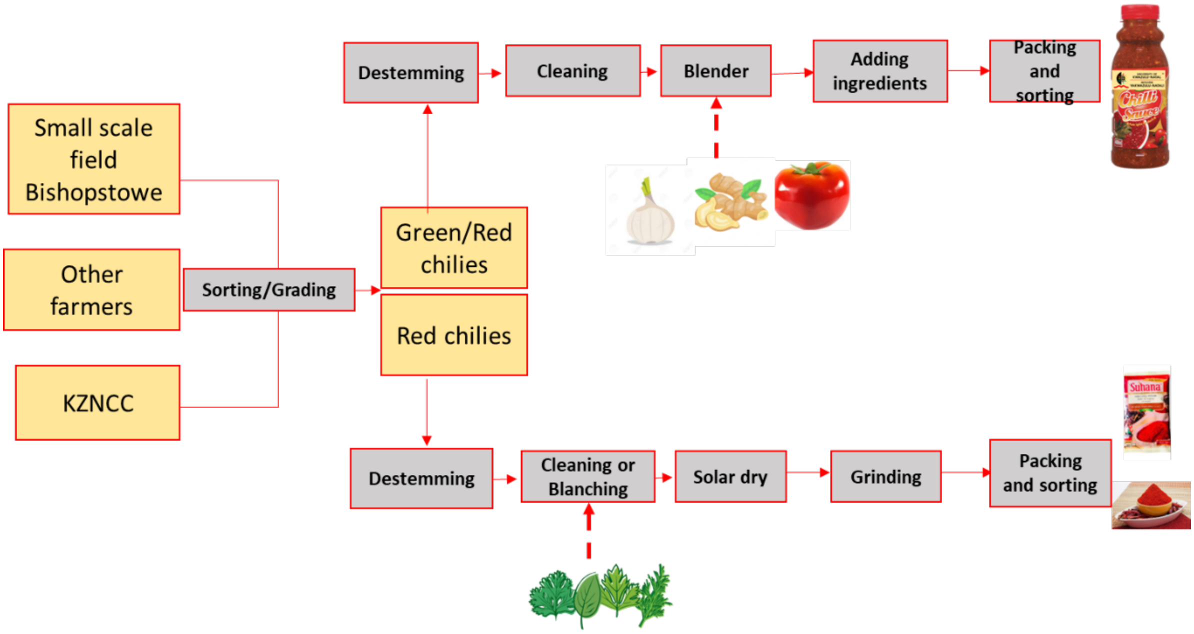

Figure 7.4. A schematic diagram of proposed agro-processing chilli peppers into paste (green chillies) and powder (red chillies).

7.6.2 Materials and methods

The production and management of chillies is described in Section 6.2.2. Ripe chillies were harvested in February 2023 by hand picking after attaining 95% maturity level. These were sorted to remove damaged, mistakenly picked green, and shrivelled chillies. Half of the harvested chillies were blanched and analysed for ascorbic acid and capsaicin content according to standard methods. The second harvest was done in May and used for the blanching experiment. Sorted chillies were divided into two equal portions; one of it was blanched and the other one was washed in ice water. Blanching was carried out by soaking the chillies in hot water at 90 °C for 2 minutes (Figure 7.5) according to methods by Romauli et al. (2023). The other portion was quickly immersed in ice-cold water for 1 minute to stop biochemical processes (Kamal et al., 2019).

Figure 7.5. First stage of the chillies blanching process – immersion in hot water at 90 °C for two minutes.

The two batches of blanched and unblanched chillies were dried in a greenhouse equipped with a fan for ventilation (Figure 7.6). The air temperature was monitored at 2 pm daily using a thermometer (maximum radiation). The chillies moisture content was determined gravimetrically. A sample of the chillies was weighed and dried at 70°C until constant mass is attained. The final weight of the chillies was measured, and moisture content was calculated according to Equation 1:

$$\text{Moisture content} = \frac{M1 - M2}{M1} \qquad \textbf{Equation 7.1}$$

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Where M1 is the moisture content before oven drying and M2 is the moisture content after oven drying.

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Figure 7.6. Improvision of solar drying technology (blanched and unblanched chillies) in a greenhouse environment free from external disturbances such as extreme weather conditions and rainfall.

Chilli colour intensity was measured using a stereomicroscope integrated with computer software (Leica Application Suite 4.0). Harvested chillies were placed on a white plain paper background on the stereomicroscope stage. The working distance was set at 25 mm. Red, Green and Blue (RGB) measurements were recorded for two chillies in triplicate for each treatment. A Leica DFC 450C camera integrated with the stereomicroscope was used to capture the images (Mandizvo and Odindo, 2019). Colour intensity was measured on fresh washed chillies and, blanched and unblanched dried chillies. The tri-stimulus values (RGB) were converted to HSL according to Mandizvo and Odindo (2019) by standardizing RGB values. The following equations were used.

$$Nr = \frac{R}{R+B+G}$$ **Equation 7.2**

$$ng = \frac{G}{R+G+B}$$ **Equation 7.3**

$$nb = \frac{B}{R+G+B}$$ **Equation 7.4**

Where nr, ng and nb are normalized values between 0 and 1, with nr + ng + nb = 1. Conversion from RGB to HSL was achieved by using the following equations:

$$H=2\pi - Cos^{-1}((0.5 \times ((nr-ng)+(nr-nb)))/(\sqrt{((\pi 〖r-ng)〗 ^2+(nr-nb)+(ng-nb))}))$$ **Equation 7.5**

$$S = 1 - 3 \times maximum\ (nr, ng, nb)$$ **Equation 7.6**

$$L = (R+G+B)/(3 \times 255)$$ **Equation 7.7**

Samples were prepared by grinding the dried chillies using a coffee maker (Figure 7.7). The chillies were blended into a fine powder and used to extract ascorbic acid and capsaicin. All chemicals were All the reagents, standards (capsaicin >95%; from *Capsicum* sp., ascorbic acid), and solvents used were of high degree of purity, purchased from Sigma-Aldrich (St. Louis, MO, USA).

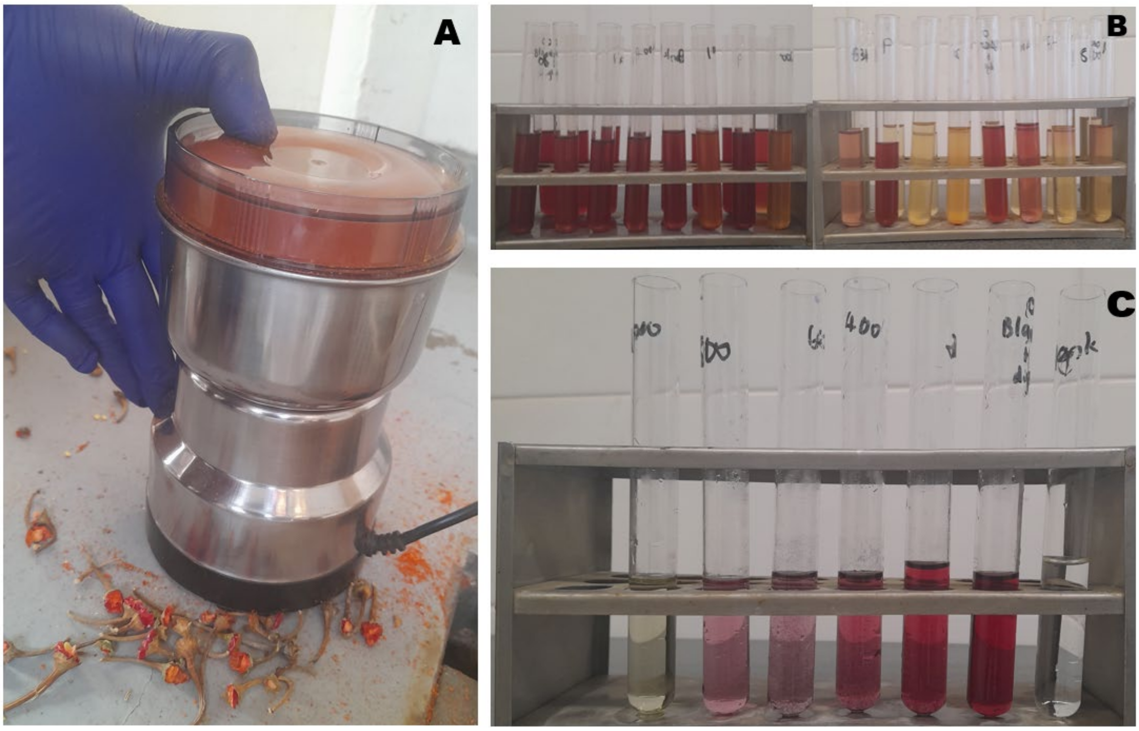

Figure 7.7. Sample preparation by grinding chillies using a blender in preparation for ascorbic acid and capsaicin extraction (A), ascorbic acid extracts from chillies for analysis using spectrophotometer (B) and Capsaicin content determination (in progress).

Ascorbic acid was measured according to methods by Desai and Desai (2019), with slight modification. A sample powder (1 g) was added to 9 mL of metaphosphoric acid (1%) and sonicated in ice for three (3) minutes. Samples were centrifuged (Avanti J-265 XP, Beckaman Coulter, Indianapolis, IN, USA) at 10,000 rpm (4℃) for five minutes. A volume of 1 ml extract was added to 8 mL of 2,6-dichlorophenolindophenol dye (0.025%). Samples were done in triplicate and incubated in the dark at room temperature for 10 minutes. Absorbance was measured with a spectrophotometer (Shimadzu Scientific Instruments Inc., 130 Columbia, MD, USA) at 515 nm. A blank of 1% metaphosphoric acid was used and a standard curve was drawn using ascorbic acid standards ranging from 0 to 1000 µg/ml. Ascorbic acid was expressed as mg/100 g dry mass.

Data collected was subjected to analysis of variance (ANOVA) using GenStat statistical analysis software 20th edition (VSN International, Hempstead, UK). Means were separated using the Fisher's protected least significant difference (LSD) when treatments showed significant differences at 5% level of probability. Principal component analysis (PCA) and the Kaiser-Meyer-Olkin measure of sampling adequacy were performed based on the correlation matrix using XLSTAT (XLSTAT 2020.5.1.1075). The loading factors derived from the PCA were used to identify variables that have a strong relationship with a particular PC. Principal component biplots were created to examine correlations between fertiliser nutrient source, post-harvest treatment and nutritional attributes to guide have information on whether human derived fertilisers can be used for high quality chilli production for small scale processing.

7.6.3 Results and discussion

Chillies are an important source of ascorbic acid and capsaicin. Understanding how post-harvest treatment such as blanching and the use of HEDFs affects the nutritional qualities of chillies is of paramount importance. The present study determined the relations between nutritional quality (ascorbic acid content) and its relationship with colour changes in blanched and unblanched chillies produced using different HEDFs under greenhouse conditions. The study further assessed the potential pathogen contamination levels for the chillies with regards to *E. coli* on freshly harvested chillies.

7.6.3.1 Colour, moisture content and ascorbic acid content

Hue, saturation, and lightness were significantly different ($p<0.01$) amongst all treatments (Table 7.4). Hue, saturation, and lightness ranged from 2.67 to 359.67°, 74.00 to 99.00, and 28 to 57.33% respectively. Higher hue values were observed in fresh and unblanched dried chillies. Blanched chillies had the lowest hue values. Five chilli colours were identified using the Reichs-Ausschuß für Lieferbedingungen und Gütesicherung (RAL) system. The colour with the highest frequency was brown-red, having a frequency of 5 and this was observed in fresh chillies (Table 7.4)

Colour intensities significantly varied between fertiliser and blanching treatments ($P<0.05$). The urine and chicken manure treatments had the brightest colour (tomato red) with a hue value of 10 and 12° respectively. Meaning that urine and chicken manure provided adequate nutrients to support lycopene (red pigment) synthesis through a series of biochemical processes. Bright colour is the most preferred by customers, making the blanching a favourable postharvest treatment for chillies to be ground into powder. These results concur with the findings of Tri et al. (2021), who observed brighter colour in chillies blanched in a solution of sodium metabisulfite ($Na_2S_2O_5$) and citric acid solution for 30 minutes.

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Table 7.4. Hue, saturation, lightness, and RAL colour codes for fresh chillies planted using different nutrient sources and post-harvest treated by blanching.

Nutrient Source	Post-harvest treatment	Hue (°)	Saturation (%)	Lightness (%)	RAL	Colour name
Control	Fresh	357.7^{de}	74.3^{a}	49.7^{e}	3011	Brown red
Chicken manure	Fresh	356.7^{d}	76.7^{ab}	49.7^{e}	3011	Brown red
Urine	Fresh	356.7^{d}	74.0^{a}	49.3^{e}	3011	Brown red
Co-compost + Urine	Fresh	356.7^{d}	75.3^{ab}	54.0^{ef}	3011	Brown red
Fertiliser	Fresh	358.0^{de}	78.0^{b}	50.3^{e}	3011	Brown red
Control	Blanched	5.00^{b}	97.67^{fg}	39.33^{cd}	3004	Purple red
Chicken manure	Blanched	12.00^{c}	99.00^{g}	54.00^{f}	3013	Tomato red
Urine	Blanched	10.00^{c}	98.67^{g}	57.33^{f}	3013	Tomato red
Co-compost + Urine	Blanched	2.67^{a}	92.00^{de}	34.00^{bc}	8012	Red brown
Fertiliser	Blanched	5.00^{b}	93.67^{de}	42.33^{d}	3004	Purple red
Control	Non-blanched	358.33^{de}	88.00^{c}	34.33^{bc}	8012	Red brown
Chicken manure	Non-blanched	359.67^{de}	91.00^{cde}	28.00^{a}	4007	Purple violet
Urine	Non-blanched	358.33^{de}	93.67^{de}	28.00^{a}	4007	Purple violet
Co-compost + Urine	Non-blanched	359.00^{e}	94.33^{ef}	39.33^{cd}	3004	Purple red
Fertiliser	Non-blanched	358.00^{de}	90.33^{cd}	31.33^{ab}	8012	Red brown
p-value	-	**<0.001**	**<0.001**	**<0.001**	-	-
LSD (0.05)	-	**2.238**	**3.448**	**5.800**	-	-

*Means in the same column followed by the same letter are not significantly different, while figures with different letters are significantly different according to Fisher's test (P < 0.05). LSD = Least Significance Difference *RAL = Reichs-Ausschuß für Lieferbedingungen und Gütesicherung.

After 14 days of drying, the blanched chillies appeared brighter compared to the unblanched chillies (Figure 7.8). The chilli skin became transparent such that the seeds were visible especially in the urine treatment. The blanched chillies had a lighter colour compared to the unblanched chillies.

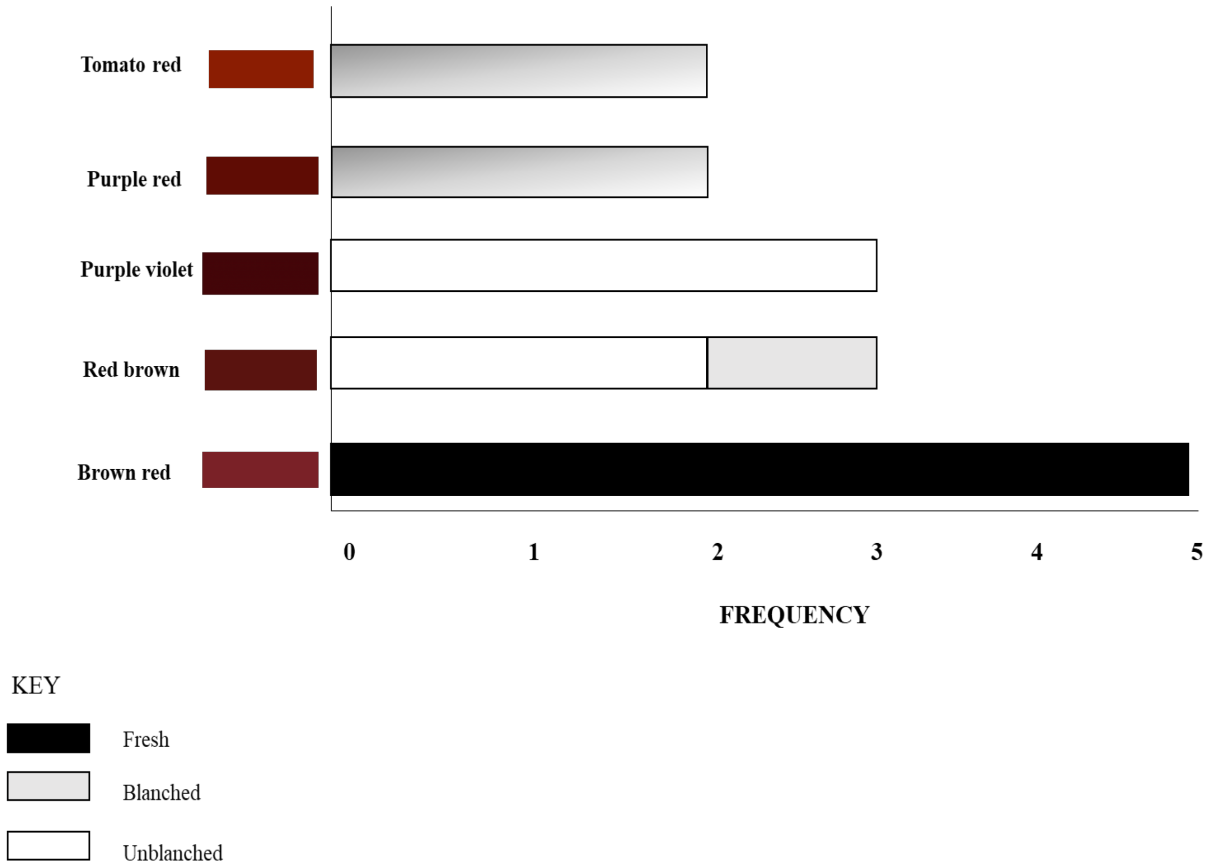

Figure 7.8. Frequency distribution of colour among pods to compare blanching and no blanching (control) planted based on the Reichs-Ausschuß fur Lieferbedingungen and Gütesicherung colour system.

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There was a significant interaction ($p<0.001$) between nutrient source and post-harvest blanching treatment on chilli moisture content (Figure 7.9). Fresh chillies from all nutrient sources had the highest moisture content ranging from 83.7 to 85.3%. The moisture content of dried chillies for both blanched and unblanched chillies ranged from 6.1 to 10.8%. The blanched chillies had lower moisture content in all nutrient sources compared to the unblanched chillies.

Moisture content is an important parameter for the shelf life of chillies. Lower moisture content result in longer shelf life. Optimisation of the moisture content limits the development of pathogenic microorganisms. The dried chillies moisture content ranged from 6.1 to 10.8% which met the standard (11%) suggested by Tri et al. (2021). Blanched chillies for all treatments had lower moisture content compared to unblanched chillies. By softening the cell wall and displacing entrapped air from the chillies, blanching ensures that chilli tissue dries more easily and faster (Romauli et al., 2023). To meet the minimum requirement for moisture content, blanched chillies can be dried for less time, thus reducing exposure to heat, and preserving quality attributes such as ascorbic acid and capsaicin. It is important to continuously monitor the moisture in chillies over time. If moisture is monitored, blanched chillies would take less time to reach the minimum threshold requirement for chillies. These results are consistent with the findings of Romauli et al. (2023) who observed blanching minimised drying time in red chillies. Moisture content is important because it determines the physical and chemical quality of the chillies. At moisture content below 4%, colour and taste are lost and at moisture content above 11%, mould grows easily (Toontom et al., 2012). In another study by Tri et al. (2021), sun drying resulted in higher moisture content (10.13%) compared to drying with a shade (9.8%) in chillies blanched in water over, while cabinet drying had the lowest moisture content of 7.91%.

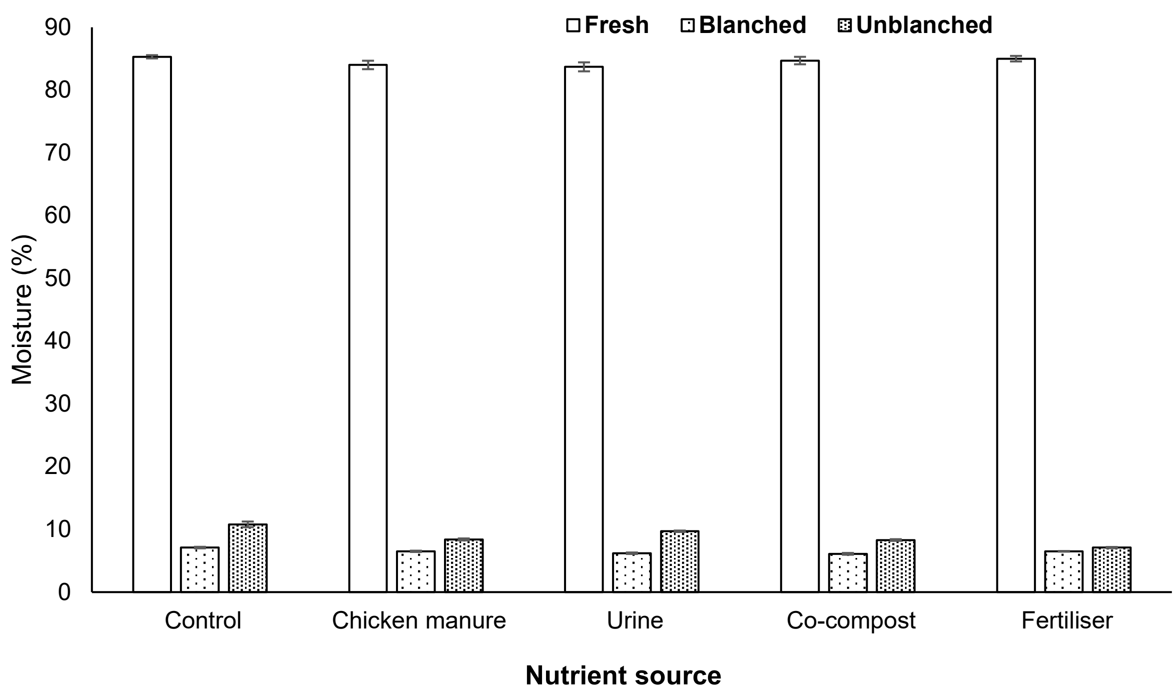

Figure 7.9. Moisture content of fresh, dry blanched and unblanched chillies

The ascorbic acid content of chillies planted with different nutrient sources significantly different (p<0.001) (Figure 7.10). The chillies from co-compost + urine had the lowest ascorbic acid content (52.5 mg/100 g).

There was a significant interaction (p<0.001) in post-harvest treatment and nutrient source in ascorbic acid content (Figure 7.10). Fresh chillies had the highest ascorbic acid content ranging from 88.76 mg/100 g (co-compost + urine) to 177.52 mg/100 g (fertiliser). Ascorbic acid decreased significantly in all treatments after blanching and solar drying (56.16 to 63.72 mg/100 g), but values for all treatments were higher that unblanched dried chillies (11.08 to 41.67 mg/100 g). In both postharvest treatment methods, and fresh chillies, fertiliser recorded the highest and co-compost + urine recorded the lowest ascorbic acid contents.

Ascorbic acid content was highest in fresh unblanched chillies (Figure 7.10). According to Food and Agriculture Organisation (FAO), food having more than 112.5 g/100 g fresh mass of ascorbic acid could be considered potential sources of vitamin C. Fresh chillies planted with chemical fertiliser had an ascorbic acid content of 177.5 mg/100 g (Figure 7.9) indicating a good source of ascorbic acid for nutritional value. Postharvest treatments that expose the chillies to heat result in degradation of heat sensitive ascorbic acid. In addition, ascorbic acid is water soluble hence any treatment involving water leaches the vitamin C into the water (Owusu-Kwarteng et al., 2017; Popescu and Avram, 2018). This explains higher ascorbic acid in freshly harvested chillies compared to dried ones. Ascorbic acid is oxidised to dehydroascorbic acid at high temperatures. As a result unblanched dried chillies had lower ascorbic acid content compared to blanched ones. This was also caused by the fact that enzymes that degrade ascorbic acid will still be active until moisture is reduced to levels that cannot sustain enzyme activity after drying. Blanching inactivates polyphenol oxidase, peroxidase, and lipoxygenase resulting in preservation of ascorbic acid and slows the loss of flavour (Anoraga et al., 2018). This implies that processing fresh chillies into paste and sauce capitalises its nutritional value. Drying chillies minimise its nutritional value but depending on the market conditions and demand which might favour chilli powder, blanching should be done to minimises ascorbic acid loss.

The ascorbic acid content in chillies was highest in the fertiliser treatment and lowest in the co-compost and urine treatment (Figure 7.10). This could be attributed to readily available N from inorganic fertiliser as well as low N losses from the use of unstabilised urine (Section 6.2.2). Nitrogen availability affects phosphorus uptake. Meaning that applied inorganic fertiliser played a role in the synthesis of glucose which is the main precursor for ascorbic acid synthesis. Adding co-compost to a soil already containing organic C increased the C pool in the soil. Several enzymes such as glucose-6-phosphate isomerase., mannose-6-phosphate isomerase, mannose-1-phosphate guanylyl transferase, GDO-mannose pyrophosphorylase, and L-Galactose-1-phosphate phosphatase that are involved in the synthesis of ascorbic acid require phosphorus (Villa-Rivera and Ochoa-Alejo, 2023). However, in this case P was comparably higher in co-compost and chicken manure than inorganic fertiliser treatment (Figure 6.6), further nullifying P deficiency as a causative factor for poor ascorbic content. These findings further support that organic amendments are mostly used as soil conditioners which should be used in complement with either inorganic fertiliser as recommended in Section 6.3.5. In addition further studies on the interaction between co-compost and stabilised urine are needed to validate if urine alone failed to provide adequate nutrients when used with co-compost.

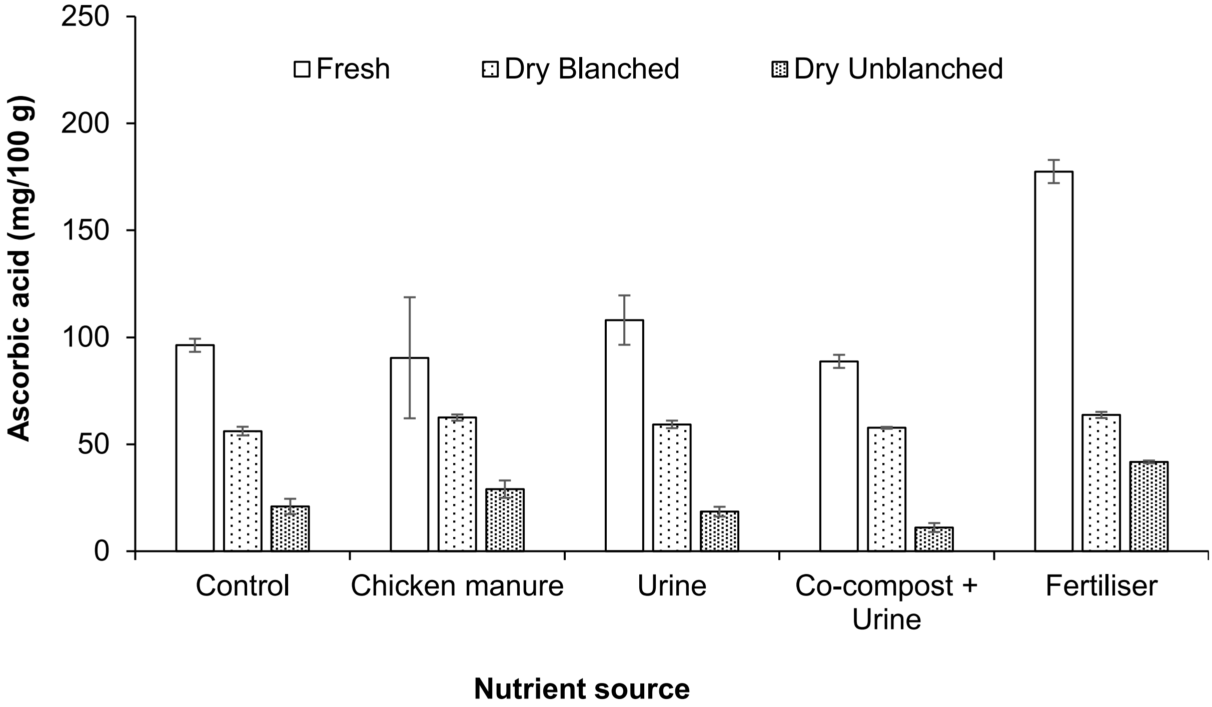

Figure 7.10. Ascorbic acid content of fresh, dry blanched and unblanched chillies.

A principal component analysis for the fresh, blanched and unblanched dried chillies was carried out to understand the relationship between colour and ascorbic acid in relation to different nutrient sources used (Figure 7.11).

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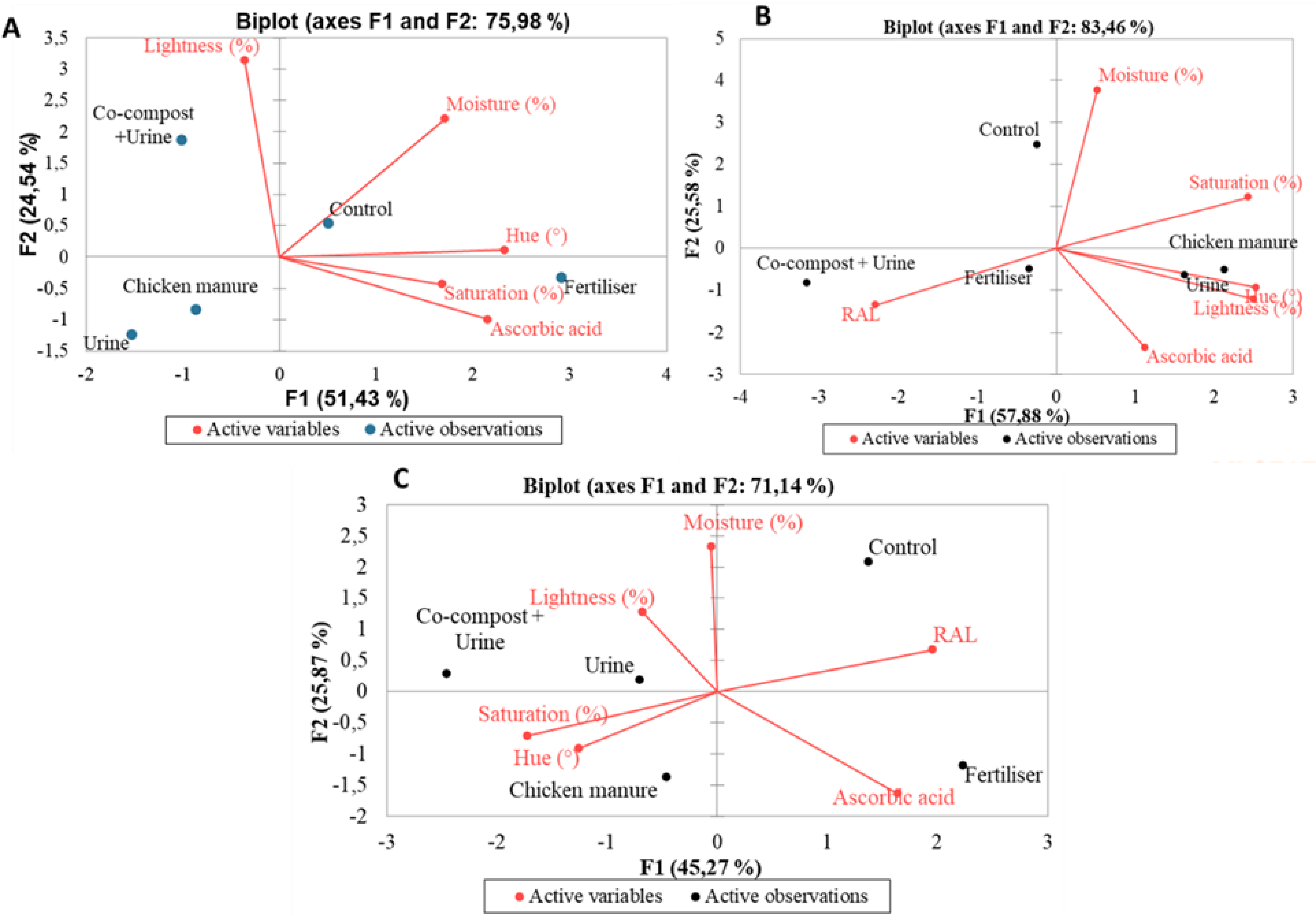

Figure 7.11. Principal component analyses showing the relationship colour, moisture, and nutritional quality in fresh chillies (A), blanched chillies (B), and unblanched chillies (C).

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7.6.3.2 Effects of temperature and drying time

Drying was carried out over 18 consecutive days and the daily temperature measured at 2 pm is show in Figure 7.12 below. The lowest temperature was 22 °C and the highest temperature reached was 39 °C. The drying was carried out in winter where temperatures are normally lower. The moisture content under the cold weather conditions met the standards of less than 11% indicating that drying is possible during winter. However, longer drying time increases contamination risks as indicated by other studies where total pathogen plate count was higher in chillies exposed to conventional drying for longer periods of time. In other studies, drying took as little as 5 and 8 days using solar hybrid and convectional systems respectively (Romauli et al., 2023). This implies that renewable energy based drying technologies such as simplified greenhouse solar drying may be used for chilli drying. This is a sustainable solution considering high solar potential in Southern African region and energy insecurity in low-income communities leading to recurrent power cuts (Jadhav et al., 2017).

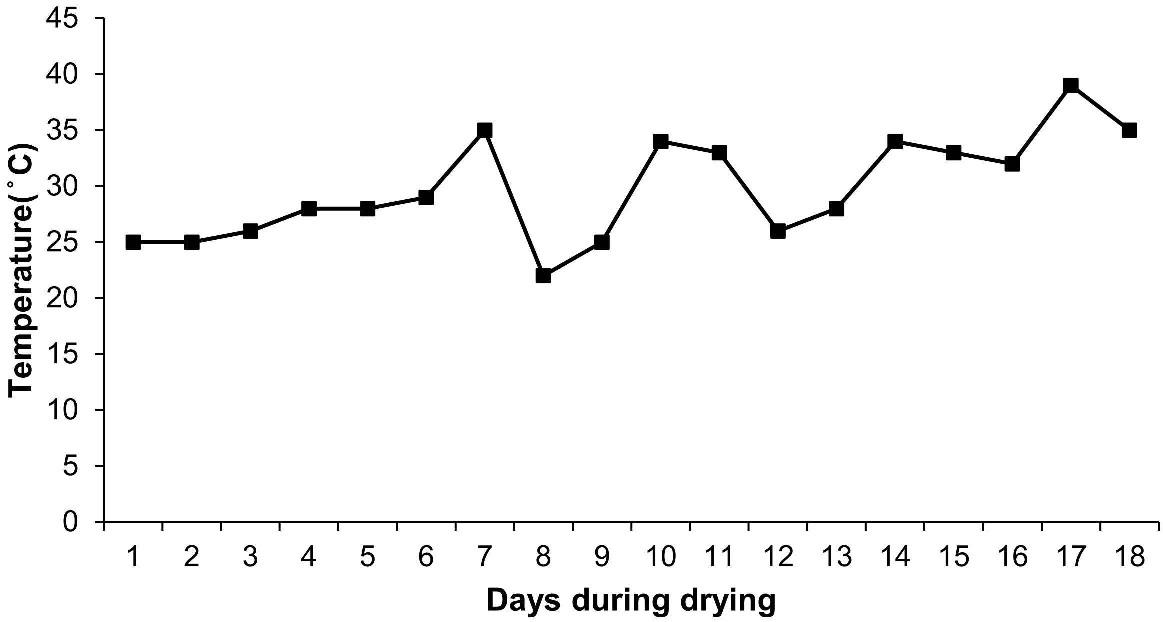

Figure 7.12. Monitoring solar energy received during drying chillies using daily temperatures (readings taken at 2 pm).

7.6.3.3 Pathogen contamination in chillies

The *E. coli* found in all treatments were below the minimum thresholds. Very low counts of *E. coli* (<1 MPN/100 g) were detected on pods harvested from the plants and even those picked from the ground reported very low counts from the co-compost + Urine treatment which had 2 MPN/100 g (Table 7.5). The most used indicator of faecal pollution is *E. coli* (Edberg et al., 2000). The guidelines for wastewater reuse states that *E. coli* limit for agricultural use is <1 MPN/g. The recommended *E. coli* counts in food products is less than 20 MPN/g *E. coli*

(Institute of Medicine and National Research Council (US), 2003). This is important in producing food products that are not harmful to consumers in compliance with the South African Foodstuffs, Cosmetics and Disinfectants Act of 1972 (DOH, 2023). Despite such positive results, picking up from the ground is generally unhygienic and should be avoided as emphasised in the multi barrier approach of the Sanitation Safety Plan (WHO, 2016).

Table 7.5. *E. coli* in chillies harvested from the plant and the ground grown using different nutrient sources.

	***E. coli* (MPN/100 g)**	
	On the plant	On the ground
Control	<1	<1
Chicken manure	<1	0
Urine	<1	<1
Co-compost + Urine	<1	2
Fertiliser	<1	<1

*MPN, Most Probable Number

7.7 Conclusions and recommendations

7.7.1 Conclusions

- Chillies, onions, cabbages and Swiss chard are the crops selected by most of the participants followed by carrots and beetroot and lastly one group selected maize, dry bean and potato.
- Several small-scale processing opportunities have been identified and these include, in chronological order, maize processing (samp, instant porridge, soup, fresh maize and stock feed), dry bean mixed with samp, potato processing (fried chips and baby food), vegetables (mixing carrots, green beans and baby corn) and some other crops were identified without any information on potential small scale processing opportunities (cabbage and Swiss chard).
- The majority proposed primary agro-processing of vegetables such as chopping and packaging of spinach followed by cutting and chopping of onions and cabbages. Lastly the other groups proposed processing of vegetable salads from tomato and chilli chutney, sliced or grated beetroot, making dry and fresh French fries, roasted maize, canned beans and chilli sauce.
- Small scale farmers are resource constrained to operate at economies of scale to meet market demands.

- Stakeholders needed in agro-processing were identified from the farming systems, post-harvest handling and marketing. The interaction of these stakeholders and partners is crucial for a sustainable agro-processing business. The research institution play a role in moderating transdisciplinary activities.
- Agro-processing can be a key integral component of an economically sustainable circular bioeconomy centred around intensive jobs creation and improved livelihoods across the value chain.
- Fresh chillies have more ascorbic acid content compared to dried chillies and this expected to further decline at higher rate if blanching is not done.
- The treatments affected the colour saturation with high lycopene synthesis reported in chicken manure and urine treatments. This was further enhanced by blanching.
- Blanching increased the chillies drying rate as well as the energy efficiency of the drying process.
- The study proved that solar drying using a simplified greenhouse structure can sustainably be used to dry chillies rather than using electricity or wood fire.
- The ascorbic acid content in chillies was low in co-compost treatment compared to conventional fertilisers.
- Chillies produced using co-compost and urine are safe to consume because the *E. coli* levels on the chillies were below limits of 20 MPN/g.

7.7.2 Recommendations

- The farmers should be organised to produce enough to meet market demands. Alternatively, an agro-processing hub can be operated by a private businessperson to provide a market for small scale farmers.
- The public private partnerships are needed to spearhead uptake of circular bioeconomy interventions.
- Market research for the selected value chains should be done to identify profitable value chains.
- Agroprocessing can be done to prevent post-harvest losses but in a way may compromise the nutrient content. For example, when nutrients such as ascorbic acid matters it is best to process fresh chillies into chilli paste.
- Pretreatment processes such as blanching are crucial to produce chilli powder.
- The heat generated during the grinding of chillies to powder should be kept as low as possible to prevent ascorbic acid degradation. More studies should be done to optimise the blanching temperature and drying conditions for maximum ascorbic acid retention. Furthermore, agronomic studies on optimising the co-compost application rate for

higher ascorbic acid content and other quality parameters such as beta-carotene in chillies when using soils with different inherent soil fertility and organic carbon contents.

7.8 Challenges and mitigation strategies

Some of the crucial components of the study that could not be reported and impending include:

- **Market Analysis**: Conduct a thorough market analysis to understand the demand for processed agricultural products. Identify potential markets, including local, regional, and international buyers.
- **Promotion and Marketing**: Develop marketing strategies to promote the processed products, both locally and internationally. Certifications such as organic, fair trade, or sustainable can add value to the products.
- **Some value chains literature is outdated and difficult to find:** Although facing challenges in getting crucial key informants from the government departments on board to gather state of art information, the team will try conduct a supplementary scoping review to address outstanding issues.

8 RECOMMENDATIONS FOR SAFE, LEGALLY, SOCIALLY ACCEPTABLE AND ENVIRONMENTALLY SUSTAINABLE HUMAN EXCRETA RECOVERY AND REUSE PRACTICES.

8.1 Introduction

The project used a transformative approaching in supporting the transition to a circular bioeconomy. The overall aim is to integrate sustainable human excreta management as a component of food system by closing a nutrient while minimising excessive extraction of natural resources vital for current and future generations. Five key areas formed part of the study and these include elucidating barriers and enablers to support bioeconomy transition, assess the application of advanced treatment processes to treat wastewater for unrestricted agricultural use, recover the urine products and fortify organic fertilisers for safe and legal commercial and agricultural use, assess the fertiliser value of HEDFs in accordance with indigenous agricultural systems and propose small scale technologies for value addition of commonly grown crops.

8.2 Conclusions

Assessing the community attitudes, perceptions and barriers towards the use of waste-based fertiliser products for crop production.

A scoping review was conducted and the major findings were:

- South African legal framework supports the use of HEDF. The major challenge is that most policies are implemented in silos, lacking coherence across all governmental organs. Various waste and food value chain stakeholders which might guide for a successful implementation of a legal, acceptable, viable and safe pilot projects identified and characterized were regulatory boards (SABS, CGSA), governmental institutions (DALRRD, DFFE, DWS, DTIC, DWYPD, DOH), private entities (Commercial farmers, Retailers) and local municipalities (Msunduzi municipality). However, there is no coordination across the stakeholders to speak one language: the CBE. Even the project could not successfully get hold of some of these stakeholders for participation.
- Lack of institutional interests is a challenge. Most local municipalities and research institutions are centred around municipal solid waste with little or no attention given towards human excreta.
- Social perceptions and attitudes are not barriers if the end users are given assurance that the HEDFs are safe to use when certified by regulatory authorities. In addition, farmers need to be assured that the HEDFs have some advantages over conventional

practices, citing environmental, financial and health benefits such as saving fertiliser costs, effects on soil health and minimising amounts of untreated waste that is entering the environment. Adoption and implementation of this principles needs adequate education and awareness.

- Apart from substantial technological advancement, South Africa has put in place adequate best practices and guidelines for agricultural use of human excreta derived fertilisers. The use of human excreta derived fertilisers is not limited to human health risks. This is due to established best practices such as the WHO Sanitation Safety Plans (SSP) approach. Despite the availability of protocols to manage health risks, for example the multi-barrier approach risk assessment and implementation of the SSP, its implementation by farmers is difficult, posing health risks across the food value chain. In this regard, excreta treatment to meet WHO standards for unrestricted agricultural use is needed.
- Economic viability of circular bioeconomy interventions might be a barrier. Interventions such as co-composting are profitable if done at scale but this is challenge for small scale entrepreneurs. Some of other identified challenges affecting existing agricultural systems include lack of title deeds, lack of access to loans to invest in state of art technologies and technical constraints to run viable agribusiness projects, lack of information on value addition and reliable markets.
- In this case there are potential indirect economic gains such as improved resource efficiency, cleaner environment and reduction in public health hazards.
- Commitment of farmers is one the barriers identified. The project successfully engaged with women and youth cooperatives from Vulindlela, Appelsbosch and Sobantu communities. However, stakeholder/member interests have prohibited some implementation and active participation of cooperatives in these CBE innovations.

To apply advanced waste treatment methods in human wastes such as excreta materials and activated sludge, monitoring and evaluating the availability of micropollutants and pathogens, and their subsequent prevalence in soils and possible transfer into plant tissues.

Technological readiness is an important aspect of the CBE toolkits. In this instance application of advanced treatment technologies to treat wastewater for eliminating micropollutant and pathogens was done. The major findings are thus reported in this section:

- The use of TiO_2 photocatalysis significantly reduced BOD, soluble COD, humic levels, and pathogens while increasing the pH and DOC.

- Significant pathogen regrowth was seen after four days of storage, suggesting potential challenges in maintaining microbial control under TiO2 photocatalysis.
- Ozonolysis treatment significantly reduced BOD, soluble COD, humic, and turbidity and eliminated the pathogens while increasing the pH and DOC. Notably, the absence of pathogen regrowth after four days of storage demonstrated the ability of ozonolysis to sustain improved microbial control.
- UV photolysis resulted in marginal reductions in BOD, turbidity, and pathogens, with increased pH, DOC, and humic levels. After four days of storage after photolysis treatment, a slight pathogen regrowth was seen.
- In comparison, ozonolysis proved to be the best AOP that would fully treat the AF effluent to meet the required wastewater standards for agricultural use.
- The removal of pathogens from technologies such as co-composting and fortification of co-compost with alkali urine could meet standards for unrestricted agricultural use. There were no pathogens observed on seedlings made using DEWATS effluent. The same was observed for chillies that were picked up from the ground in co-compost amended soils.

The recovery of bioresources such as struvite and biosolids from the human excreta and sewage sludge was done.

- Undiluted urine yielded more high-quality struvite with higher phosphorus content.
- Fortification of sewage sludge/green waste co-compost with dried urine increased its fertilizer value to comply with the South African Fertilisers, Farm Feeds, Agricultural remedies and Stock remedies Act no 36 of 1947 for registration as an "organic fertiliser mixture".
- The fortified organic fertilizer mixture had very high pH which makes it a good alkaline fertiliser
- The urine can be recovered from public places but logistics is the main constraint that may affect establishment of a sustainable business for struvite or dried urine production.

To grow selected crops to test the fertiliser value of the waste-based bioresource products, impacts on soils, crops, and the environment.

Best agricultural practices in the use of HEDFs to optimise crop yields and agronomic benefits should be codeveloped from context specific practices. The study tested the application of best agricultural practices on the use of HEDFs based on farmer production systems identified during participatory exercises. A field study was done under dryland farming and following findings are reported:

- The climatic conditions monitored during the growing period were conducive for chilli growth and yield as per the historical data.
- The yields of chilli peppers were comparable amongst all fertiliser treatments including the control ones.
- Most aspects of soil health; microbial communities, microbial enzymatic activity and soil chemical analyses did not significantly differ in response to amendments except for microbial activity, organic C and extractable P. Microbial activity was significantly higher in chicken manure amendments. The organic C and extractable P significantly increased in co-compost. The extractable P was higher in both co-compost and chicken manure.
- There were no signs of borehole water contamination as shown by absence of pathogens and mineral nutrients (N and P) in the analysed samples.

The study investigated the use of DEWATS effluent and sewage sludge co-compost for vegetable seedling production.

- The use of DEWATS effluent and co-compost increased seedling vigour. Meaning that there is potential for HEDFs to produce healthy and strong seedlings with faster establishment and subsequent economic returns.
- All the treatments including conventional seedling production practices did not meet the Fertilisers, Farm Feeds, Agricultural remedies and Stock remedies Act no 36 of 1947 requirements for a good growing media in terms of supporting 80% germination except for Swiss chard. However, all the treatments were above the minimum standards (>50%) for an ideal growing media as all supported at least 60% germination. Meaning that the co-compost does not exhibit phytotoxicity.
- The same legislation and seedlings production best practices requires the growing media and seedling to be free from root to diseases. *Phytopythium spp.* was found in co-compost and some conventional media samples. Poor post co-composting handling have been the major reason for damping off pathogens in the tested samples. *Fusarium spp.* was also found in tomato seedling irrigated with all water sources including the municipal freshwater. Meaning that integrated disease management practices including disinfecting irrigation prior to use needs to be considered regardless of water source. The use of co-compost and DEWATS effluent complied with the Occupational Health and Safety Act of 1993 that there were no health hazardous traces of *E. coli* on seedlings to expose farmworkers during handling.

The study tested the phytotoxicity of co-compost on crops with a presumption that it could not support chilli and tomato growth and yield.

- Results obtained showed that the co-compost has no negative effects on crop growth and physiology when used as a growing media.
- Further to that its ability to improve soil properties and fertiliser use efficiency was shown in a poor sandy soil.
- Failure of chillies and tomatoes when grown in co-compost growing media. Consultation with the farmers showed that they are facing problems in purchasing agrochemicals which lead to intense diseases attack that destroyed the crops.
- Appelsbosch farmers had an advantage of being led by an AGRISETA accredited leader who provided them with proper guidance on best agricultural practices.
- Co-compost can be used with inorganic fertilisers to act as a soil conditioner while the latter is a source of nutrients.

To propose small-scale processes for value addition of locally produced crops using the recovered waste-based bioresource products.

- Several crops were selected during the engagements with farmers and stakeholders. The main crops that were identified include chillies, onions, cabbages, Swiss chard, carrots, beetroot, maize, dry bean and potato. However, the processing options were maize processing (samp, instant porridge, soup, fresh maize and stock feed), dry bean mixed with samp, potato processing (fried chips and baby food), vegetables (mixing carrots, green beans and baby corn) chopping and packaging of Swiss chard, onions and cabbages.
- There is an opportunity for linking agroprocessing with local food production. The salad crops are part of the local dishes included in restaurants.
- Stakeholders needed in agro-processing were identified from the farming systems, post-harvest handling and marketing. The interaction of these stakeholders and partners is crucial for a sustainable agro-processing business. The research institutions play a role in moderating transdisciplinary activities.
- Postharvest handling and processing technologies such as blanching and solar drying of chillies was assessed. The drying process was found to reduce the ascorbic acid content and this process is lower if blanching is not done.
- The treatments affected the colour saturation with high lycopene synthesis reported in chicken manure and urine treatments. This was further enhanced by blanching. The

ascorbic acid content in chillies was low in co-compost treatment compared to conventional fertilisers.

- On an energy efficiency point of view the drying process should happen at a lower rate while using lesser energy. Blanching chillies increased their drying rate and energy efficiency of the drying.
- The study proved that solar drying using a simplified greenhouse structure can sustainably be used to dry chillies rather than using electricity or wood fire.
- Chillies produced using co-compost and urine are safe to consume since the *E. coli* levels on the chillies were below limits of 20 MPN/g.

8.3 Recommendations

Assessing the community attitudes, perceptions and barriers towards the use of waste-based fertiliser products for crop production.

- Farmers are capacitated through trainings on agribusiness management, linked to sound and viable local and international markets, incorporation of value addition practices in their farming systems and provided with opportunity to access loans from microfinancing companies.
- Current governmental policies should be revised. Enforcing strict laws for sustainable excreta management from the municipal level. Furthermore, all governmental departments, regulators and other stakeholder should come together and draft policies that explicitly allow the use of human excreta for food crops.
- Farmer engagement should consider indigenous practices and norms as well as involvement of beneficiaries in each stage of the transition process.
- Technical capacity building on best practices for human excreta use by target groups can be administered through trainings and progress monitoring of circular bioeconomy interventions are needed to ensure compliance.
- More studies are needed on integrating advanced treatment technologies as obligatory components of the Sanitation Safety Plans to treat wastewater to pathogen levels that allow WHO unrestricted agricultural use. Economic feasibility of incorporating advanced treatment technologies in different components should also be assessed.
- Business models are important to assess economic viability and provide evidence-based information for private sector investors to engage in profitable circular bioeconomy activities. Private investors are crucial actors in technological investments through public-private partnerships.

  The competition for linear economy products is higher than circular bioeconomy interventions.

- The future on access to international markets such as the European union is promising, with such countries considering circular bioeconomy policies to include their trade partners.
- The farmers should be educated about maximising profits from such interventions through diversification of activities at the farm level, e.g. value addition and production of high value **crops.**

To apply advanced waste treatment methods in human wastes such as excreta materials and activated sludge, monitoring and evaluating the availability of micropollutants and pathogens, and their subsequent prevalence in soils and possible transfer into plant tissues.

- The advanced oxidation processes have potential to remove organic pollutants and pathogens. There are lot of issues to be considered, e.g. the effect of process parameters such as pH, time, and initial concentration on these AOPs
- The operation and expenditure costs as well as potential for business models by linking with high value crop value chains.
- Studies on micropollutants selected based on their relevance in the specific excreta stream are pending and the results will be reported in the final report.
- The HEDFs such as co-compost and DEWATS effluent can be used without problems on pathogen contamination. The co-compost and effluent can be used for seedling production. The co-compost can be used for agriculture without spreading *E. coli.*

The recovery of bioresources such as struvite and biosolids from the human excreta and sewage sludge was done.

- The DU and co-compost fortification produces a high pH product that can be added sulphate containing compounds to moderate the pH. Sub Saharan countries are battling with acidic soils so the fortified product can be used as a soil amendment.

- The production of fortified co-compost is financially feasible if operated by a private company which afford to invest in equipment for large scale production. More research on sustainable business models is required in terms of understanding the supply chains dynamics, logistics and market dynamics. Especially if smallholder farmers are to be included.

- Commercial production of the fortified co-compost at viable scale needs strong investment in resources and linkages with feedstock sources.

To grow selected crops to test the fertiliser value of the waste-based bioresource products, impacts on soils, crops, and the environment.

- With the current systems small scale farmers can produce adequate chillies during the summer periods because the climatic conditions are not limiting. The challenge comes in winter when they must meet market demands. It is crucial for them to invest in irrigation systems so there must be It is crucial for them to invest in irrigation systems so there must be guided in ways to obtain infrastructural development loans from organisations such as ADA as one of the measures to transitioning to resilient circular bioeconomy.
- The full potential attributes of human excreta derived fertiliser could not be expressed in dryland agriculture. Therefore more research should be done to understand the impacts HEDFs on soil health under irrigated cropping systems as part of science and innovation in optimising management systems in a circular bioeconomy. In addition the soil health impacts in terms of microbiome shifts, nutrient cycling and emissions should be assessed in the long term.
- Organic amendments such as co-compost are good sources of soil bioavailable P even in dryland agriculture but caution must be given in managing pollution from surface run off especially in clayey soils in sloping areas.
- On the sanitation safety point of view the study did not lead to groundwater contamination on point PPL6 of Figure 4.1. However, long term monitoring is still needed at 6 months interval.
- The HEDFs can be used by small scale farmers to produce their own healthy and strong seedlings that establish very fast in the field, thus, saving input supply costs and contributing to their food systems resilience.
- The presence of damping off pathogens in co-compost growing media and treated wastewater cannot be pinned to the materials as these can also be detected even in commercial conventional materials. Therefore, best practices to treat and prevent post co-composting contaminations are needed and may be difficult to implement by small scale farmers. This may limit commercial seedling production by small scale entrepreneurs as they hardly meet minimum seedling certification standards. They can produce for local markets within their networks.
- With proper guidance from private sector, the SGASA and the certification boards and DALRRD extension there is potential to support communal entrepreneurs produce high quality seedling using HEDFs.

To propose small-scale processes for value addition of locally produced crops using the recovered waste-based bioresource products.

Agro-processing can be a key integral component of an economically sustainable circular bioeconomy centred around intensive jobs creation and improved livelihoods across the value chain if:

- The farmers should be organised to produce enough to meet market demands. Alternatively, an agro-processing hub can be operated by a private businessperson to provide a market for small scale farmers. The public private partnerships are needed to support technological investments.
- Market research for the selected value chains should be done to identify profitable value chains applicable to specific farmers.
- Technological selection in small scale processing should consider aspects such as energy requirements and optimising quality aspects to meet customer satisfaction. For example the use of renewable energy such as solar during drying is a sustainable option in an energy insecure country like South Africa. Some customers are conscious about their nutrition for example the ascorbic acid is higher in green chillies. In this regard a strong market research is needed.
- The heat generated during the grinding of chillies to powder should be kept as low as possible to prevent ascorbic acid degradation. More studies should be done to optimise the blanching temperature and drying conditions for maximum ascorbic acid retention. Furthermore, agronomic studies on optimising the co-compost application rate for higher ascorbic acid content and other quality parameters such as beta-carotene in chillies when using soils with different inherent soil fertility and organic carbon contents.
- Agro processing is not limited to manufacturing products for sale but there is an opportunity for linking it with indigenous or local practices, e.g. production of chicken, goats or rabbits for restaurants can be a sustainable solution. This is an easy and profitable way of capitalising on local markets rather than worrying about the stringent international ones. In addition there is opportunity for rural development if such activities are marketed to the international world, whereby the linkage with the international world is through tourism.

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APPENDICES

Appendix 1. The participatory rural appraisal process with cooperatives.

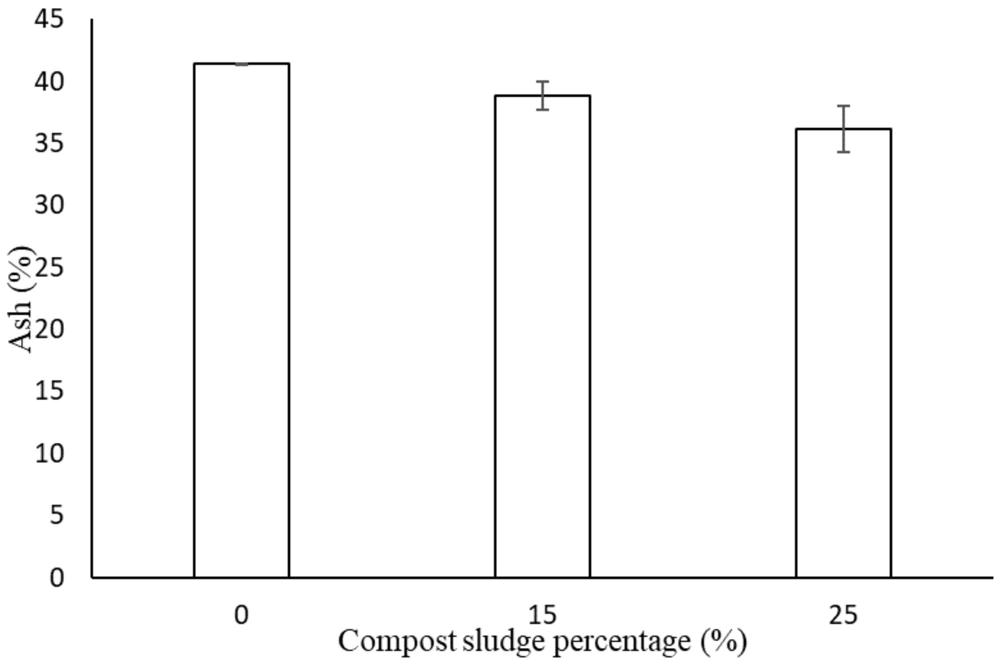
Item	Discussion points
Land tenure	Ownership at Appelsbosch
Soil analysis	Do you analyse your soils?
Water quality and availability	Water source
Financial stability	Access to loans or other financial incentives
Crop management	Inputs: planting material, labour, fertilisers, agro-chemicals, Power: electricity, fossil fuels, solar source Irrigation: drip, sprinkler or surface
Crop protection	Weeding, pests and disease control
Marketing	Post-harvest handling, reliable availability and value addition
Social issues	Theft, safety

Appendix 2. Co-compost struvite fertiliser mix (A) and co-compost DU fertiliser mixes at different struvite and DU application rates

Appendix 3. Co-compost characterisation

Faecal sludge (%)	Organic green waste (%)	pH $_{(H2O)}$	pH $_{(KCl)}$	Moisture (%)
15	85	7.8[b]	6.5[b]	38[a]
25	75	6.8[a]	6.3[a]	47[b]
p-value		<0.001	<0.001	0.004
cv (%)	-	1.6	1.6	0.9
s. e. d	-	0.096	0.077	0.474

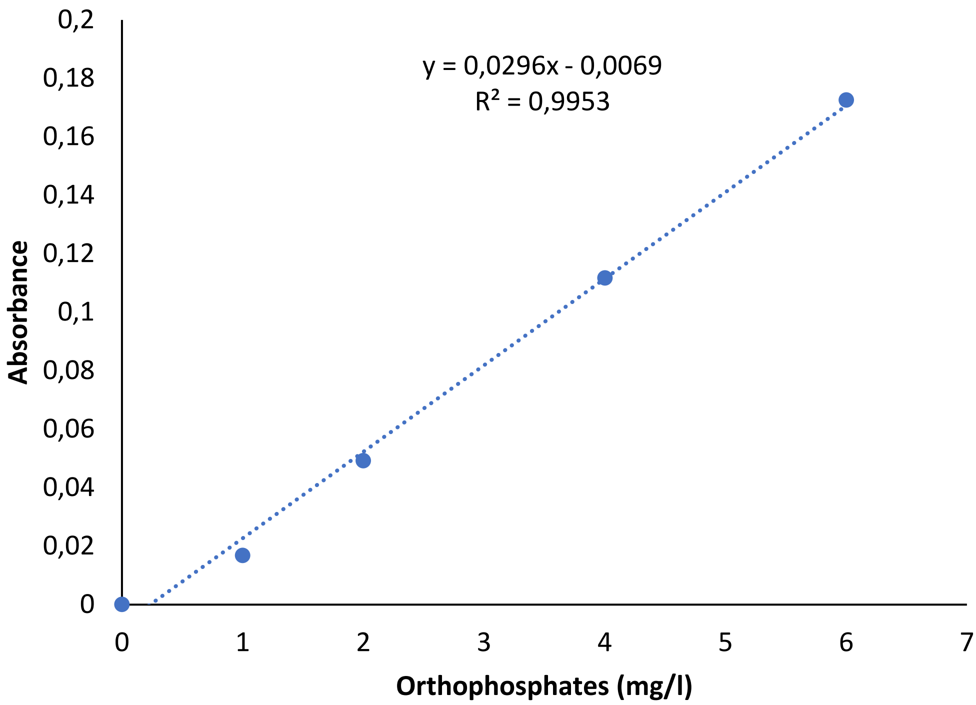
Appendix 4. Co-compost ash content



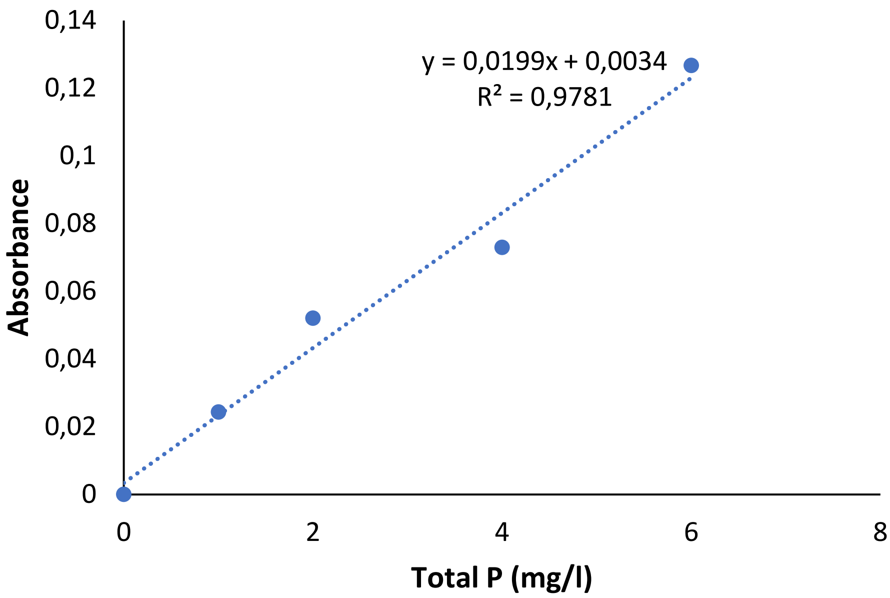
Appendix 5. Co-compost total P, orthophosphates, and total N.

Faecal sludge (%)	Organic green waste (%)	Total P (mg kg^{-1})	Orthophosphates (mg kg-1)	Total N (%)
15	85	637.7		1.25 a
25	75	1508.8		1.29 a
p-value	-	<0.001		0.445
cv (%)	-	0.3		4.8
s. e. d	-	97.1		0.049

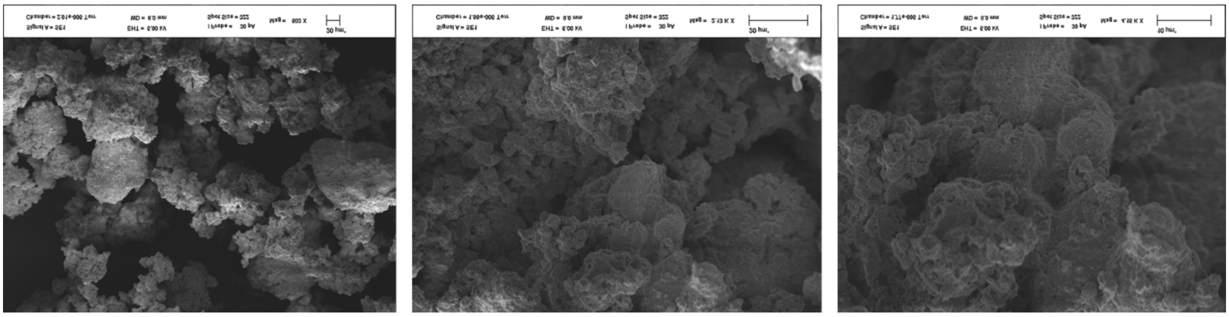
Appendix 6. Standard curve for orthophosphates in struvite



Appendix 7. Standard curve for total phosphorus in struvite



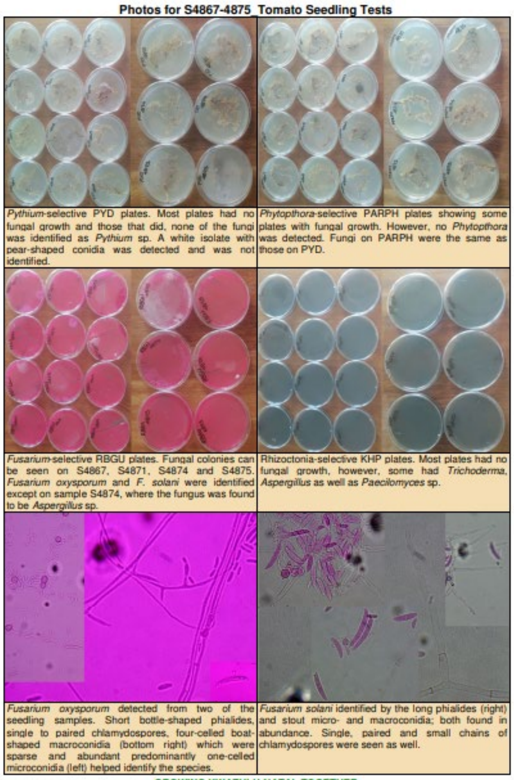
Appendix 8. SEM images of dried urine



Appendix 9. Minimum nutrient requirements for enriched organic and organic fertilisers

NAME OF PRODUCT	METHOD OF MANUFACTURE	MINIMUM NUTRIENT CONTENT: OTHER REQUIREMENTS		DECLARATION OF FORMS, SOLUBILITIES AND OTHER NORMS		
		TOTAL	PER ELEMENT	N	P	K
1	2	3	4	5	6	7
Organic fertiliser or organic fertiliser mixture	A product formed by mixing the different organic fertilisers without addition of inorganic fertilisers	40 g/kg	Nonspecific	Nonspecific	Citric acid soluble P (Optional) Total P	Nonspecific
Enriched organic fertiliser	A product that is formed by mixing organic and inorganic fertilisers with an organic component of at least 500 g/kg (1,75 x C)	100 g/kg	10 g/kg	Total N	Citric acid soluble P (Optional) Total P. If raw phosphate is a component of the mixture, the application for registration must specify the fineness and origin of the raw phosphate and citric soluble P must be given	Total K

Appendix 10. Growing media and seedlings pathogen test results



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Appendix 11. Maize analysis of variance tables

Variate: Leaf_number

Source of variation	d.f.	(m.v.)	s.s.	m.s.	v.r.	F pr.
Treatment	8		570.817	71.352	22.91	<.001
Time_Wks_After_Emergence	6	(4)	625.699	104.283	33.48	<.001
Treatment.Time_Wks_After_Emergence	48	(32)	68.679	1.431	0.46	0.999
Residual	187	(110)	582.500	3.115		
Total	249	(146)	1636.400			

Variate: Plant_height_m

Source of variation	d.f.	(m.v.)	s.s.	m.s.	v.r.	F pr.
Treatment	8		7.36210	0.92026	16.55	<.001
Time_Wks_After_Emergence	10		86.82401	8.68240	156.11	<.001
Treatment.Time_Wks_After_Emergence	80		3.58230	0.04478	0.81	0.876
Residual	295	(2)	16.40675	0.05562		
Total	393	(2)	112.72458			

Variate: Chlorophyll_content

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Treatment	8	17352.09	2169.01	99.85	<.001
Time_Wks_After_Emergence	10	18196.95	1819.70	83.77	<.001
Treatment.Time_Wks_After_Emergence	80	4251.68	53.15	2.45	<.001
Residual	297	6451.96	21.72		
Total	395	46252.68			