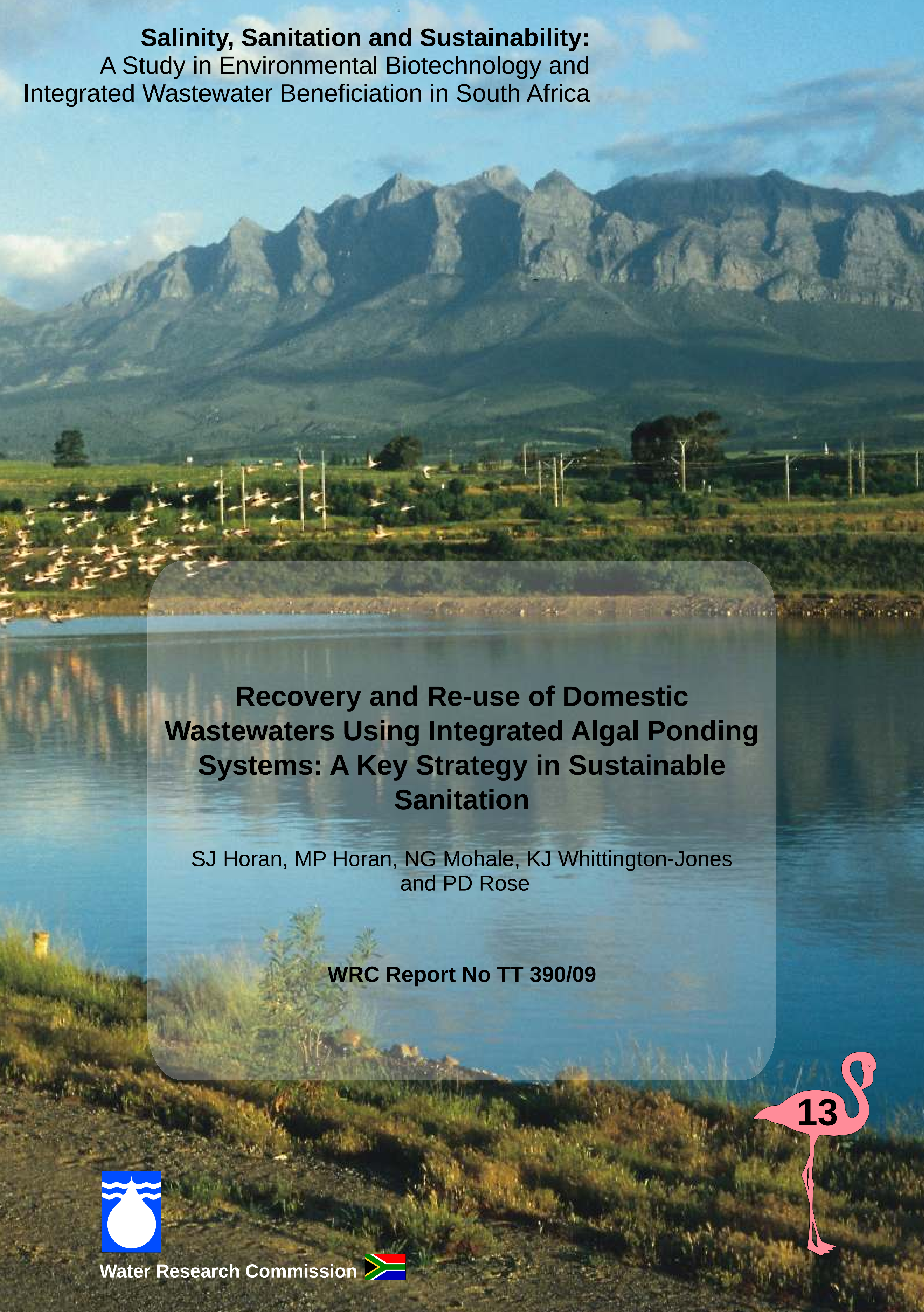

Salinity, Sanitation and Sustainability:
A Study in Environmental Biotechnology and Integrated Wastewater Beneficiation in South Africa

Recovery and Re-use of Domestic Wastewaters Using Integrated Algal Ponding Systems: A Key Strategy in Sustainable Sanitation

SJ Horan, MP Horan, NG Mohale, KJ Whittington-Jones and PD Rose

WRC Report No TT 390/09

13

Water Research Commission

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A Study in Environmental Biotechnology and Integrated Wastewater Beneficiation in South Africa

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Cover Photograph:

Flamingoes on tannery wastewater ponds at Mossop Western Leathers Co., Wellington, South Africa. The presence of Phoenicopteridae, including both the Greater and Lesser Flamingo, is an important indicator of healthy and naturally functioning saline aquatic ecosystems. This flock occupied the ponding system shortly after commissioning the novel *Spirulina*-based Integrated Algal Ponding System which had been developed for the treatment of tannery wastewaters. This apparent seal of environmental approval became an icon for the studies which followed in this series.

Photograph by Roger Rowswell, whose observation of this system, over a number of years, was instrumental in the initiation of these studies.

RECOVERY AND RE-USE OF DOMESTIC WASTEWATERS USING INTEGRATED ALGAL PONDING SYSTEMS: A KEY STRATEGY IN SUSTAINABLE SANITATION

Report to the
Water Research Commission

by

S J Horan, M P Horan, NG Mohale, KJ Whittington-Jones and PD Rose

on behalf of

Environmental Biotechnology Research Unit
Rhodes University
Grahamstown

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EXECUTIVE SUMMARY

1. BACKGROUND

The degradation of water resources through ineffective and insufficient wastewater treatment has substantial social and environmental impacts. However, this also has direct economic effects which jeopardise the sustainability of future development in water-scarce countries such as South Africa. Poorly treated water is a major contributor to water pollution with elevated oxygen demand, and nutrient and bacterial loadings, leading to eutrophication and destabilisation of important aquatic ecosystems (Horan, 1990).

An investigation of the status of small sewage treatment works (STW) in the Eastern Cape (designed to treat less than 1Mℓ.day^{-1}) showed that these were largely poorly operated and inadequately monitored leading to the release of undertreated effluent into the environment. Lack of maintenance of infrastructure, inadequate operator skills, insufficient monitoring capacity and insufficient forward planning were cited as reasons for poor performance (Antrobus, 2002). A subsequent study by Snyman *et al* (2006) confirmed that a similar situation applied throughout South Africa and indicated that immediate intervention was necessary for 30% of STWs in South Africa to avoid crisis situations, such as the outbreak of waterborne diseases, and a further 66% required intervention in the short to medium term. The consequences of the situation have been borne out in the tragic loss of life in Delmas in 2006 and elsewhere (Graham, 2006; DWAF, 2003) due to gastrointestinal infections.

2. THE INDEPENDENT HIGH RATE ALGAL POND

The Integrated Algal Ponding System (IAPS) has been intensively studied as a low-cost appropriate sewage treatment technology (Rose *et al*, 2002). In a 9-year study of the system at the Environmental Biotechnology Research Unit (EBRU) at Rhodes University, the High Rate Algal Pond (HRAP), as a component unit operation of the IAPS, was found to be effective as a stand-alone unit for the tertiary treatment of wastewater, particularly where primary and secondary treatment was not achieving required standards for effluent disposal (Wells, 2005). The Independent HRAP (IHRAP), as it became known, was shown to be particularly effective in the disinfection functions of tertiary treatment and could consistently produce water with *E. coli* counts of <1CFU.100mℓ^{-1}. In this way the use of chlorine, ozone or other chemical disinfectant treatments are obviated. In addition to effective disinfection, ammonia and phosphate levels were also reduced below discharge standards at 1.4 mg.ℓ^{-1} and 2.3 mg.ℓ^{-1} respectively (Wells & Rose, 2006; Wells, 2005).

It has been proposed that the IHRAP would provide a low-cost intervention that could be applied immediately as a ‘firewall’ barrier between existing, poorly performing sewage works and the receiving environment. This could enable treatment plants to meet discharge standards and deal effectively with the substantial public health threats both rapidly and at extremely low cost.

3. ALGAL BIOMASS UTILISATION IN HORTICULTURAL APPLICATIONS

Algal biomass is produced as a by-product of the IHRAP treatment process and substantial literature exists on the use of various algal types (including macrophytic algae such as kelp sea weed) as a source of fertiliser and plant growth stimulant applications in horticulture (Arthur *et al*, 2003; Donelan, 1988; Metting, 1988; Senn, 1987; Featonby-Smith and Van Staden, 1983). In addition to NPK and minerals, algal extracts are thought to provide plant hormones such as auxins and cytokinins, as well as chelating functions (Kelpak, 2005; Davis, 2004; SeaGro Superkel pamphlet, 2004; Arthur *et al,* 2003; Zhang and Schmit, 2000; Zhang, 1997; Crouch and Van Staden, 1993a; Borowitska, 1988; Donelan, 1988; Senn, 1987).

The potential use of algal biomass produced in the IHRAP treating sewage wastewaters for use in plant growth stimulation applications was investigated in the studies reported here. Where this would be shown to be a useful plant fertiliser, the combination of a well-treated and disinfected water, with the biomass recovery as a fertiliser, could provide the basic inputs for the development of a horticultural enterprise and sustainability in wastewater treatment operations. Laboratory and field trials in algal biomass recovery and its use in nutrient enrichment in horticultural applications thus formed the focus of WRC Project K5/1619.
Algal biomass was harvested from the pilot-scale IHRAP at EBRU in Grahamstown, treating domestic wastewater. Laboratory-based pot trials were undertaken in a controlled environment over three growth seasons using algal biomass as a soil amendment and also as a foliar feed application in a range of vegetable types. Chemical commercial fertiliser (2:3:2 N:P:K) was applied as a control, based on equivalent nitrogen concentration.

Application of algal biomass as a soil amendment was found to significantly enhance plant growth, equivalent to that of the commercial chemical fertiliser in radishes and Swiss chard, compared with untreated soil ($p>0.05$). Radish yields were increased from an average <10g.plant^{-1} in untreated soil to 13g.plant^{-1} for soil treated with algal biomass. These results were statistically comparable to the average yield weight of radishes grown in soil treated with 2:3:2 fertiliser. The second radish harvest planted in the same previously-treated soil showed similar results, with yields increased by 60%. The increase in yield for the first Swiss chard harvest from soil treated with algal biomass compared to the untreated soil was also comparable to the increase in yield achieved with addition of fertiliser. Interestingly, the second Swiss chard harvest from the same soils (no further supplements applied) showed yields which were higher than for the fertiliser treatment. In the final harvest, Swiss chard yield from soil treated with algal biomass was on average 45g.plant^{-1} compared to <20g.plant^{-1} for the fertiliser treatment.

Laboratory-based pot trials were followed up with field trial studies. Similar results were achieved for the first Swiss chard harvest in the field trials where the yield for algal-treated soil was 15.4 tonnes.ha^{-1} compared with 10.5 tonnes.ha^{-1} in fertiliser-treated soil. Turnip yields were also slightly higher for algal-treated soil at 3.8 tonnes.ha^{-1} compared with 2.6 tonnes.ha^{-1} from fertiliser-treated soil. From the results of both laboratory and field-scale studies, it has been shown that algal biomass increases yield comparable to, and sometimes exceeding, yield increases shown with the use of inorganic fertiliser.

While the nutrient content of the algal biomass may explain some of the increased growth observed, other mechanisms of growth stimulation could play a role. This was particularly noticeable in the field trials where environmental stress factors were more varied.

A foliar feed was produced from the IHRAP algal biomass and applied to plants in a separate study. Increases in crop yield in the conditions under which it was tested were not observable. Notably, however, the commercial sea weed-derived foliar feed used as a control did not significantly increase yields under the test conditions either. While the results of these studies were inconclusive, further investigation is needed to fully examine the possibilities of microalgae-based foliar feed production.

4. INTEGRATED WASTEWATER RESOURCE RECOVERY: THE CONCEPT

The studies reported here support earlier findings that the IHRAP system may provide a technological intervention required to deal with a crisis situation in the South African sanitation and water sector (Wells, 2005). However, such an intervention has been shown to have other benefits that could also impact the economics and sustainability of small sewage treatment works in South Africa. The studies on utilisation of IHRAP treated water and algal biomass has led to the consideration of its application in an Integrated Wastewater Resource Recovery study. Here the small, underperforming sewage treatment works could recover value from the treated wastewater in the form of high quality treated effluent and algal biomass for horticultural applications. The provision of job opportunities, while also improving effluent quality, would protect the receiving environment and also the health of downstream users. Investigation of the system as a case study was undertaken with funding supplied by the United Nations Environment Programme Western Indian Ocean Land-based Activities (UNEP WIO-LaB) initiative. The Bushman's River Sewage Treatment Works and surrounding community were identified as a site for the demonstration of the concept. The small resort town frequently experiences severe water shortages and droughts, relies heavily on an expensive reverse osmosis process to meet potable water supply demands, has a very high unemployment rate, and the sewage works currently pollutes its major tourist draw-card, the Bushman's River estuary, with poorly treated effluent. A preliminary planning study was undertaken and showed that a wastewater resource recovery system pilot plant set up at Bushman's River or similar sites would not only demonstrate well-researched IHRAP technology, but would also provide an insight into entrepreneurial opportunities that would be available in horticulture, agriculture and mariculture, and therefore lead to employment opportunity and possibly the self-sufficiency, or even profitability, of sewage treatment works to the wider community.

5. RECOMMENDATIONS

Based on the above study, a provisional feasibility for the Integrated Wastewater Resource Recovery System based on the IHRAP technology has been demonstrated for the small sewage works. The laboratory studies of algal biomass utilisation and the Bushman's River case study provide the baseline for follow-up investigations. It is thus recommended that sufficient information is now available to undertake further studies at a demonstration scale for this concept. These include the following:

1. It is recommended that a demonstration plant such as that proposed in the Bushman's River case study be constructed to subject the concept to a detailed and rigorous investigation

2. A detailed economic study be undertaken into all aspects of the integrated wastewater resource recovery concept in order to gain support and confidence within the political and sanitation sectors for roll out in the developing world

3. Further studies into the plant hormones and nutrient content of the algal biomass are needed to fully understand the mechanisms behind the growth stimulation of the algal biomass when utilised as a soil amendment

4. Refined techniques of IHRAP algal foliar feed production need to be developed and tested to determine the viability of creating a high value foliar feed product equivalent to successful kelp-based products currently on the market.

CONTENTS

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- The Project Team consisted of the following people:

  - Prof PD Rose : Project Leader
  - Mrs S J Horan : Researcher
  - Mr MP Horan : Researcher
  - Mr KJ Whittington-Jones : WIO-Lab Project Leader

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LIST OF ABBREVIATIONS

AFP	Advanced Facultative Pond
ASP	Algal Settling Pond
ATS™	Algal Turf Scrubber™
BOD	Biochemical / Biological Oxygen Demand
COD	Chemical Oxygen Demand
DO	Dissolved Oxygen
EBRU	Environmental Biotechnology Research Unit
EGSB	Expended Granular Sludge Bed
HRAP	High-Rate Algal Pond
HRT	Hydraulic Retention Time
IAPS	Integrated Algal Ponding System
IHRAP	Independent High-Rate Algal Pond
N	Nitrogen
NH_3	Ammonia
NH_4^+	Ammonium Ions
NO_2^-	Nitrite
NO_3^-	Nitrate
NWA	National Water Act 36 Of 1998
P	Phosphorus
PO_4^{2-}	Phosphate
SS	Suspended Solids
STW	Sewage Treatment Works
TKN	Total Kjeldahl Nitrogen
US EPA	United States Environmental Protection Agency
WIO-LaB	West Indian Ocean Land-based Activities
WSP	Waste Stabilisation Pond
WSSD	World Summit on Sustainable Development, 2002

1 SANITATION AND SUSTAINABLE DEVELOPMENT

1.1 INTRODUCTION

Access to water and sanitation has emerged as a core target in the drive to achieve sustainable development (WSSD, 2002; State of South Africa Population Report, 2000). Inadequate provision of sanitation, as well as inefficient sewage treatment and sewage discharge, are major contributors to water pollution with elevated oxygen demand, nutrient and bacterial loadings, leading to eutrophication and the destabilisation of important aquatic ecosystems (Horan, 1990). The degradation of water resources through inadequate wastewater treatment has substantial and economic impacts which jeopardise the sustainability of future developments in water-scarce countries such as South Africa. Wall (2000) outlines two major challenges faced by developing nations in the provision of water and sanitation infrastructure. Firstly, implementation of reliable, quality services must continue in order to reduce the number of people without adequate sanitation; and secondly, the provision of these services must be delivered through environmentally sustainable means.

The workshop on Sustainability of Small Water Systems in Southern Africa, (WSSD, 2002), identified the management of small water treatment plants as "problematic" and therefore they pose sustainability problems for small communities. Inadequate attendance to technical, social and institutional issues were cited as major causes of this failure to achieve sustainability (Murray *et al*, 2004). A similar situation exists with the sustainability of small wastewater treatment systems in South Africa and particularly in the Eastern Cape (Whittington-Jones *et al*, in draft.). A model developed by Murray *et al* (2004) for small water treatment systems is equally applicable to wastewater treatment plants (Figure 1.1). The model demonstrates that all components of sustainability are inter-related and consequences of unsustainable management have escalating ecological, social and economic impacts (Murray *et al*, 2004).

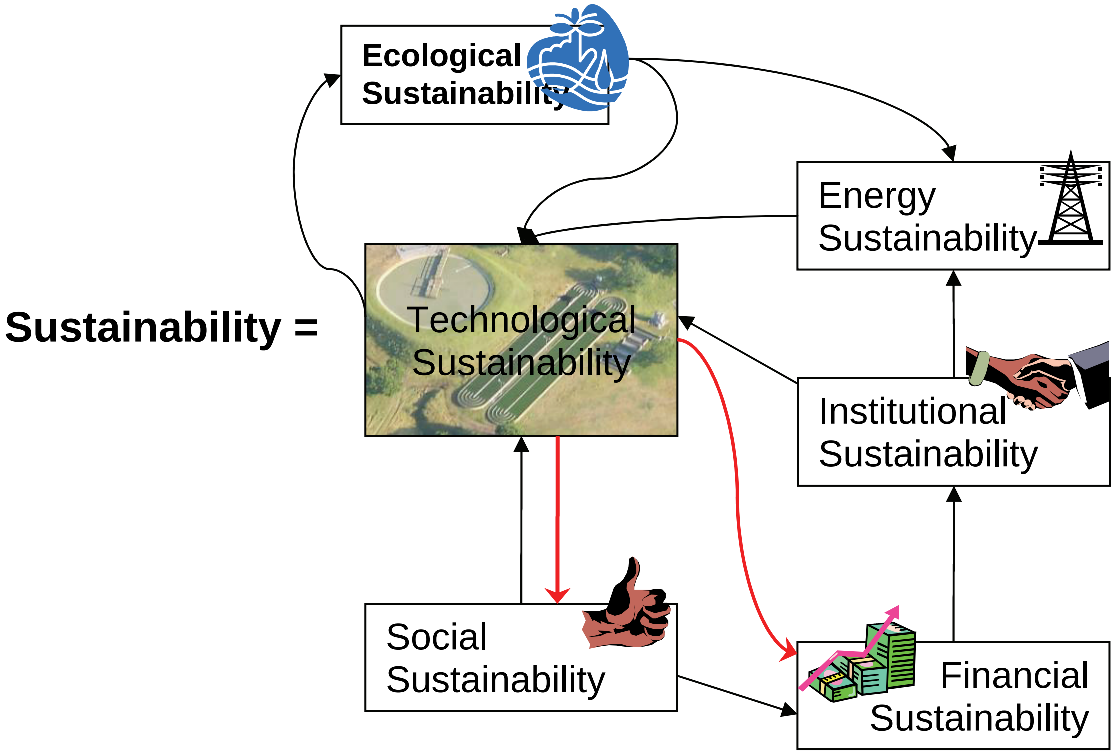


Figure 1.1: Interactions between the components of sustainability (after Murray *et al*, 2004). The red arrows indicate where Integrated Algal Ponding System technology can increase social and financial sustainability.

Conventional thinking in international development organisations is to approach financial sustainability of service provision by recovery of operational and maintenance costs through user charges (Marah *et al*, 2003). Poverty, public perception, administration and illegal connections all constitute barriers to efficient cost recovery, leading to unsustainable service provision levels and costly collapses in infrastructure and service delivery (Marah *et al*, 2003). Marah *et al* (2003) investigated practical strategies to overcome obstacles to cost recovery for water services but came to the conclusion that the primary obstacle is poverty thus making payments for service provision impossible. An alternative approach would be to ensure the wastewater treatment technology does not require onerous start-up capital, high levels of technical skills or large operational costs as is suitable for the community it serves. As municipalities in South Africa do not charge directly for sanitation (referring here to sewage treatment in particular), conventional cost recovery for the full sanitation service can only be taken from rates and taxes which depends again on income. Similar obstacles are therefore likely to exist for cost recovery for sanitation services as for water services. Thus a different approach to sustainability in these areas is needed. Considering the limitations of cost recovery in the context of a rapidly developing country, alternatives to direct cost recovery by way of charges should be considered (IRC, 2005). Alternatives to conventional wastewater treatment technologies should be weighed up to ascertain suitability and sustainability (Murphy, 2000) as outlined in Figure 1.1.

Numerous ways of recovering costs from a sewage treatment works are potentially available, including biogas production (Murphy and McKeogh, in press) and sale of sewage sludge to farmers or brickmakers (Smith and Vasiloudis, 1989). More studies are needed to evaluate these types of schemes and their applicability in the South African context. An in-depth look at skills and infrastructure would be necessary for biogas capture to determine the viability of cost recovery through biogas production. The classification of sludges and an in-depth study into the long term impacts would also have to be completed to allow sale of sludge to occur. The emphasis has to be on simplicity as, only by combining waste beneficiation with simple alternative technologies, can the sewage treatment works become more sustainable and without the burden of highly technical or costly retrofitted infrastructure. The scale of technology can also play a major role in the level of community involvement (Wall, 2002). Small-scale technology allows for greater community-based and private involvement in these water and sanitation systems (Wall, 2002).

The Integrated Algal Ponding System (IAPS) is one such low-cost, low-technology wastewater treatment system which can add another dimension to the technological, social and financial sustainability of a wastewater treatment system. The IAPS not only produces high quality effluent which ensures a safe environment, it also produces algae as a potentially valuable by-product (Rose, 2002). This is in contrast to problematic sludge production by most conventional systems (Hahn, 2001; Le Moux and Gazzo, 2001). A detailed description of the IAPS is outlined in Chapter 2. The community served by the IAPS can benefit financially by utilisation of the algal by-product and improved effluent quality, thereby facilitating community upliftment without placing a heavy financial burden at the door of the government or outside funders.

1.2 CLOSING THE NUTRIENT CYCLE

Much debate surrounds soil degradation in sub-Saharan Africa where soils are generally poor in nutrients (Koning and Smaling, 2005). Organic matter and therefore soil fertility has declined in sub-Saharan Africa due to population pressure and change in agricultural practices. Koning and Smaling (2005) describe the soil nutrient balance (Figure 1.2), showing the following factors which increase soil nutrients, which they call the “IN” factors:

1. Application of mineral fertilisers and amendments such as rock phosphates and lime
2. Application of organic fertilisers such as household waste, manure, or (indirectly) concentrates fed to livestock
3. Atmospheric deposition
4. Biological fixation of nitrogen
5. Sedimentation through irrigation or accumulation of eroded materials.

They also describe the factors which lead to soil nutrient depletion labelling these the “OUT” factors:

1. Removal of nutrients in harvested products (grains, tubers, animal products)
2. Removal of crop residues and nutrients contained within them
3. Leaching of nutrients beyond the root zone

4. Gaseous losses of N and S (denitrification, volatilisation, burning)
5. Wind and water erosion.

The sum of the IN factors minus the OUT factors will determine whether nutrients are being gained or lost in a particular soil. Using this model it can be shown how the use of algal biomass from High Rate Algal Ponds (HRAPs) used in effluent treatment with downstream agriculture may be able to address this issue.

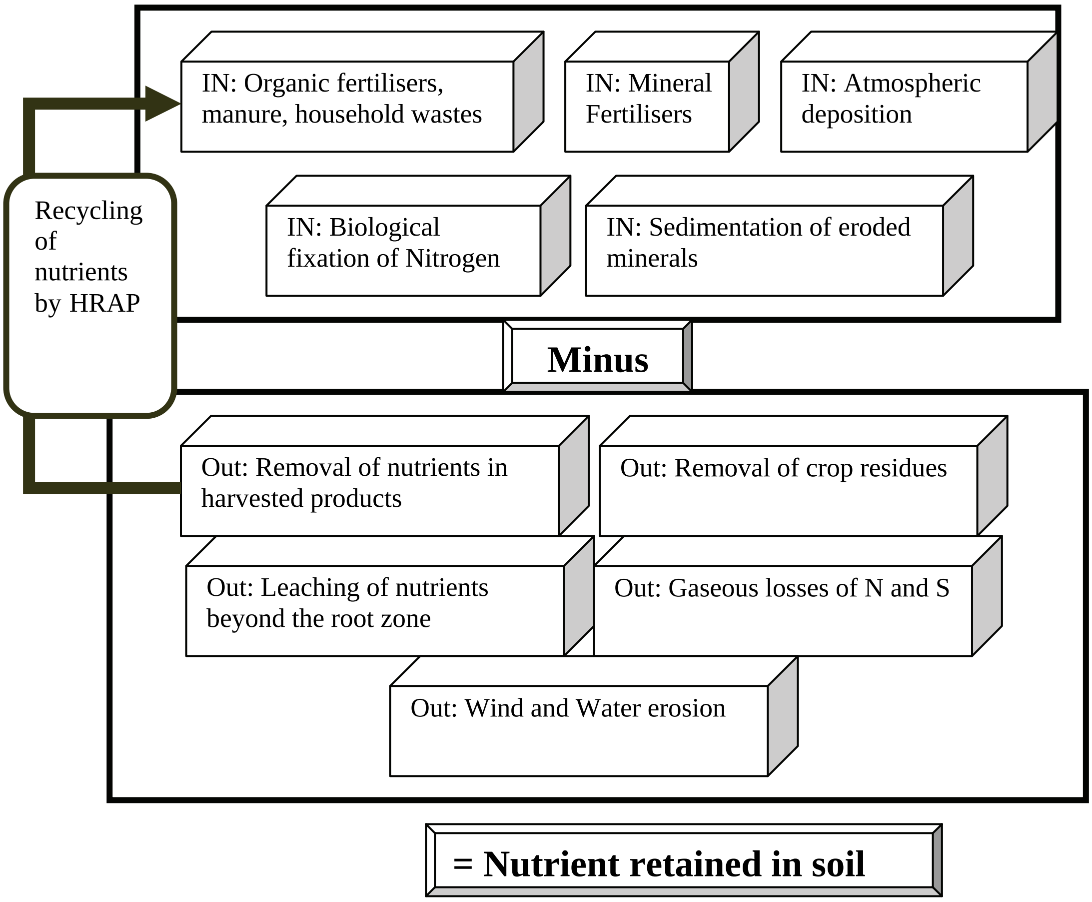


Figure 1.2: A diagrammatic summary of IN and OUT factors which lead to soil depletion. This system includes the notion of the use of algae as a soil amendment, creating a "closed loop" for at least one aspect of the soil nutrient equation. In this case it exhibits the potential of the High Rate Algal Pond in domestic effluent treatment and the subsequent use of harvested algae as a soil amendment (After Koning and Smaling, 2005).

Figure 1.2 illustrates how the recycling of nutrients via harvesting of algae from the IAPS process could address the issue of soil degradation in a closed community. There is also a question of whether the use of algae as a soil amendment can also address this problem in other ways, including increasing soil organic matter, which will not only contribute directly towards nutrients, but may also assist in building soil structure and increasing the soil's ability to retain nutrients.

Added to declining soil fertility, there is a growing water demand in urban and peri-urban environments. Niemczynowicz (1999) calls the lack of access to water resources "an ultimate poverty", and cites current and emerging challenges as the "recycling of wastewater nutrients, wastewater irrigation and urban agriculture".

According to Niemczynowicz's (1999) study, the average amounts of nutrients in wastewater in Sweden are adequate to be used in agriculture instead of, or in conjunction with, chemical or "fossil fertilisers" with phosphorous values of 0.6-0.26 kg/person.year, nitrogen values of 4.8-5.0 kg/person.year, potassium values of 4.0 kg/person.year and carbon values of 42.0 kg/person.year. Niemczynowicz (1999) states three challenges that exist in addressing urban water management through nutrient recycling and suggests that these challenges can be met by sanitation systems that do not require water and produce nutrient-rich end products safe for agricultural use as well as a means of re-using wastewater safely for agricultural irrigation.

The challenges of waterless sanitation systems is beyond the scope of this study, but creation of safe nutrient-rich end-products as well as a mechanism for safe use of wastewater for irrigation has great potential to meet the challenges to which Niemczynowicz (1999) refers.

The use of sewage as a nutrient source has been applied for centuries. Night-soil is still used directly in places like Vietnam (Needham *et al*, 1998) and China (Gandhi *et al*, 2001) as an important source of nutrients in agriculture, with far-reaching hazards on the health of the people. Rural people particularly were found to have high parasite loads due to working in the fields where this practice is common. These health impacts highlight the need to treat sewage before its use in this manner.

The treatment of sewage through biological means has been thoroughly researched and developed in recent history with the primary focus on treatment of wastewater and removal of excess nutrients, to preserve health and the ecology of the receiving water body (Horan, 1990). The high nutrient concentration and organic content of the sludge by-product has also long since been valued as a resource for agriculture and horticulture, and as a low-cost alternative to inorganic fertilisers and commercial compost. In the past, sparsely populated agricultural communities enabled the spreading of sludge on agricultural land as a feasible practice. With the growth of large cities and large sewage treatment works this 'resource' has become concentrated far from agriculture production. In addition nutrient recovery via re-use of sewage sludge in agriculture and land farming has become unpopular due to concerns regarding odour, pathogen, heavy-metal contamination and public perception (Hahn, 2001; Le Moux and Gazzo, 2001). Although sometimes this perceived risk is somewhat different from actual risk, the decline in popularity of this use for sewage sludge disposal means that valuable nutrients are lost and that sludge disposal has become a major problem around the world (Hahn, 2001; Le Moux and Gazzo, 2001). The difficulty arises in recovering these nutrients in a manner which is socially, politically and ecologically acceptable and at low risk. Refocusing the function of sewage treatment to include the capture of nutrients via biomass production (Bavor *et al*, 1995) with the aim to use this biomass for its nutrient content, seems a logical solution to closing the nutrient cycle in a more acceptable manner. A life-cycle assessment can help determine the suitability of a technology to fulfil the role of closing the loop between food production and loss of nutrients out of a system (Fredriech and Buckley, 2002).

More recently the use of sewage sludge as a soil amendment and nutrient resource has come under the spotlight due to the health implications with regards to parasites and bacteriological status as well as contamination of crops with heavy metals (Snyman and Herselman, 2005). Sludge guidelines have existed in South Africa since the 1970's when they were administered by the Department of Health. These were revised in the early 90's and then managed under the Health Act (Snyman, and Herselman, 2005). Further research was prompted by increasing environmental awareness and disagreement over the guidelines between the Department of Health, the Department of Water Affairs and Forestry (DWAF), the Department of Agriculture and the Department of Environmental Affairs and Tourism (DEAT). It was then recognised that potential detrimental environmental and health effects of agricultural use of sewage sludge exist and limitations on sludge application was needed (Lötter and Pitman, 1997). The study, funded by the Water Research Commission, led to the drawing up of the 1997 guidelines entitled "Utilisation and Disposal of Sewage Sludge, Edition 1" (WRC, 1997). This defined four sludge types and permissible uses according to classification. This was promptly followed by an addendum (Addendum 1 to Edition 1, 1997) to make the 1997 guidelines more user-friendly. The 1997 guidelines were seen by sludge producers as impossible to achieve and pre-emptive in the absence of tangible scientific evidence. In addition, these guidelines were largely based on experiences of other countries and based on theoretical risks.

This precautionary approach has resulted in the problem of what to do with the nutrient-rich sludge, which often ends up in landfills. According to figures by Smith and Vasiloudis (1989), 47% of sewage sludge was being disposed to sacrificial land application, while a little more than 25% was used in a beneficial manner in South Africa. The majority of that 25% was used in municipal parks, some was sold to farmers, less-still was used on cultivated lands, with the smallest proportion being used for brickmaking (Smith and Vasiloudis, 1989). This can be blamed to some extent on the hesitancy of legislators and producers to encourage the use of sludge, as many are unsure of the dangers or of the class or 'type' of sludge permissible for utilisation according to the Guideline (Snyman and Van der Waal, 2004). The problem of disposal as well as the wasting of a recognised valuable resource prompted further research by Snyman and Van der Waal (2004) and a review of the 1997 guidelines. They discovered that despite this low sludge utilisation rate in the agricultural sector described by Smith and Vasiloudis (1989), "South African farmers using sewage sludge as a fertiliser amendment reported a 20% increase in the yield of cultivated maize and a 40% saving on inorganic fertiliser."

Sludge utilisation guidelines were revisited with the publication of 'The Guideline on the Permissible Utilisation and Disposal of Waste Water Sludge: Edition 2'. These guidelines have adopted sustainable sludge management as its guiding principle (Snyman and Herselman, 2005) while recognising the need to assess individual sewage treatment works for sludge characteristics, wastewater received, local industries and industrial effluent standards (Snyman and Van der Waal, 2004).

Nutrient recovery from human and animal waste is also possible via hi-tech solutions such as membrane filtration; membrane filtration with ion exchange and the membrane-coupled expended granular sludge bed (EGSB) reactor (Chu *et al*, 2005; Pieters *et al*, 1999). This has the advantage over conventional sewage treatment systems of retaining all microorganisms (Chu *et al*, 2005) and producing high quality effluent. These technologies require high capital and operational expenditure, high technical skills level and do not address the problem of sludge disposal, and therefore have limited applications, particularly in the developing world.

A number of ‘natural’ wastewater treatment systems have become popular, low-cost alternatives to conventional activated sludge-type systems (Nhapi, 2004) and have the potential for biomass harvest. The most well-known systems are duckweed-based pond systems (Lemna polyrhiza), water hyacinth-based systems (Eichornia crassipes) and constructed wetlands. The IAPS has been intensely studied for the past 20 years as another low-cost alternative treatment technology (Rose *et al*, 2002). All the above-mentioned systems have biomass as a by-product rather than sludge. Harvesting and use of the biomass has been explored to a greater or lesser degree for the potential for re-use of nutrients (Nhapi, 2004; Nelson *et al*, 2001, Maart, 1993) without the controversy of sewage sludge or the expenses of membrane filtration. With the number of different wastewater treatment technologies available, it becomes necessary to assess each one for sustainability, using a cradle-to-grave approach (Fredreich and Buckley, 2002).

1.3 THE SOUTH AFRICAN CONTEXT

The problem of water pollution by sewage occurs due to the lack of, or inadequacy of wastewater treatment systems. Such inadequacy is common in many South African towns (Morrison *et al*, 2001). Many rural communities in South Africa, and especially in the Eastern Cape, use water directly from rivers for domestic purposes without any treatment (State of South Africa Population Report, 2000) and it is therefore of importance that the quality of the water remains adequate for human consumption. At a minimum, water quality should be suitable for abstraction and irrigation of crops. Water is in many cases pumped and purified at great cost to municipal water suppliers The pollution of water resources increases the need for purification prior to use, thus increasing water treatment costs to users such as municipalities, farmers, as well as posing a health hazard to downstream communities.

Water pollution caused by nutrient enrichment and pathogenic bacteria has environmental, social and economic impacts. It is therefore of vital importance that wastewater is adequately treated before release into rivers or used for purposes such as irrigation. Effective treatment of sewage is a key element in maintaining clean and sustainable water resources, hence sanitation and sustainable use of the world’s water resources was one the main topics of discussion at the 2002 World Summit for Sustainable Development (WSSD). To achieve the goals and targets set at WSSD as well as comply with legal effluent standards set by the NWA and DWAF, it is first necessary to establish the status of sewage treatment works (STW) in terms of efficiency and adequacy.

1.4 OBJECTIVES

The WRC study on the utilisation of algal biomass and treated effluent from the IAPS as a key strategy in sustainable and low-cost sanitation (Project K5/1619) was undertaken in conjunction with the West Indian Ocean Land-based Activities programme project (WIO-LaB). The following combined project objectives were identified:

1. To evaluate the relevance of the IAPS and the Independent High Rate Algal Pond (IHRAP) for the treatment and disinfection of wastewaters in the Eastern Cape and broader South African and context

2. To develop and evaluate methods and techniques for the recovery and use of algal biomass from the HRAP
3. To explore and develop uses of algal biomass in horticultural employment-creation applications
4. To investigate production of a value-added product from the algal biomass, as a foliar feed in horticulture
5. To establish a demonstration IHRAP plant which would need to demonstrate the disinfection of municipal sewage effluent and provide algal biomass for the adjacent horticultural employment-creation programme
6. Use the demonstration facility to inform public and private sector representatives from South Africa as well as from participating West Indian Ocean (WIO) countries on the benefits and applicability of the IHRAP technology including the improved treatment of municipal wastewater, subsidising the treatment of wastewater and local/regional economic upliftment through links with crop production
7. To establish a working model of algal biomass and IHRAP effluent utilisation as an Integrated Resource Recovery System applied in economic upliftment
8. To build capacity in the operation of the IHRAP technology and the processing of the algal by-products. This includes training of local entrepreneurs and vegetable growers with regards to the maintenance of the ponding systems as well as the harvesting and optimal use of the algal biomass as a fertiliser for a community vegetable gardening project.

1.5 RESEARCH QUESTIONS

In order to establish the value of IAPS and IHRAP, both in terms of a sewage treatment technology and as a resource recovery technology, the main questions to be answered were identified as follows:

1. What is the status of sewage treatment in the Eastern Cape and what is the application requirement for IAPS and/or the IHRAP as a model for this and other developing countries?
2. Can the linkage of IAPS/IHRAP and the use of algal biomass and disinfected water in horticulture provide a model for sustainable sanitation in the developing world context?

2 THE INTEGRATED ALGAL PONDING SYSTEM AND INTEGRATED WASTEWATER RECOVERY OPERATIONS

2.1 INTRODUCTION

The Environmental Biotechnology Research Unit (EBRU) at Rhodes University recently completed a 9-year study of the IAPS as a low-cost and sustainable wastewater treatment process (Rose *et al*, 2002; Wells *et al*, 2006). The IAPS accords with the environmental sustainability goal of the United Nation's Millennium Development Goal (UN, 2004) as it enables sustainable water use by treating wastewater to a standard where effluent can be reclaimed in a state in which it can be reused. The principals of water and nutrient recycling needed to achieve true sustainability are encompassed in all aspects of the IAPS from low energy inputs to the potential for the utilisation of algal biomass by-product. The IAPS closes the cycle of waste to biomass while producing high quality, recyclable effluent at low input cost (Rose *et al*, 2002).

Oswald (1988, 1990, 1991, 1994) has described the development and processes of the Advanced Integrated Algal Ponding System (AIWPS) which was developed to retain advantages of Waste Stabilisation Ponds (WSP) while mitigating their shortcomings. This specialised ponding system consists of a fermentation pit contained within a primary facultative pond (PFP), one high rate oxidation pond, algal settling ponds (ASP) and a maturation pond. Rose (Rhodes University) and Hart (WRC research manager) recognised the applicability of this low cost system to South Africa and particularly to the Eastern Cape and with the support of the Water Research Commission a pilot plant was constructed in 1994 at the Grahamstown Disposal Works (Rose *et al*, 2002) Numerous configurations of advanced ponding systems were investigated and gave rise to the IAPS concept (Wells, 2005).

2.2 THE IAPS CONFIGURATION IN DOMESTIC WASTEWATER TREATMENT

The IAPS demonstration plant for treatment of domestic wastewater was constructed at the EBRU Field Station, Grahamstown (Figure 2.1). Process flow is described below. Following screening and grit removal, raw sewage enters the bottom of an anaerobic fermentation pit which is submerged in the primary facultative pond. Upflow velocity of about 1.5m/day results in a hydraulic retention time of three days and allows settling of parasitic ova, cysts and solids (Oswald, 1991). The fermentation pit is sunk at a depth of 4.5 m into the ground with vertical walls which extend 1.5m above the floor of the PFP (Figure 2.2). This prevents mixing between the PFP and the fermentation pit content thereby ensuring the pit remains a highly anoxic environment. Biogas bubbles lift some solids from the pit but break as they rise, allowing solids to resettle and creating an anaerobic sludge blanket in the pit (Wells, 2005). The long sludge-solids retention-time allows for almost complete digestion and sludge removal is seldom required (Wells, 2005).

Figure 2.1: The Integrated Algal Ponding System at the Rhodes University Environmental Biotechnology Research Unit, Grahamstown Disposal Works**.**

The effluent from the pit then passes into the primary facultative pond (PFP) where it will remain for approximately 20 days. The surface waters are aerobic which allows algae to flourish and provides an oxygen blanket over the PFP and controls odour (Oswald, 1991). Together with the fermentation pit, a reduction of up to 60% of total BOD can be achieved in this unit. Breakdown of organic material releases carbon dioxide which is utilised by the algae (Oswald, 1991).

Water treated in the PFP flows from an outlet pipe at a depth of 1m below the surface to the HRAP, which prevents any remaining floatables entering the HRAP (Oswald, 1991).

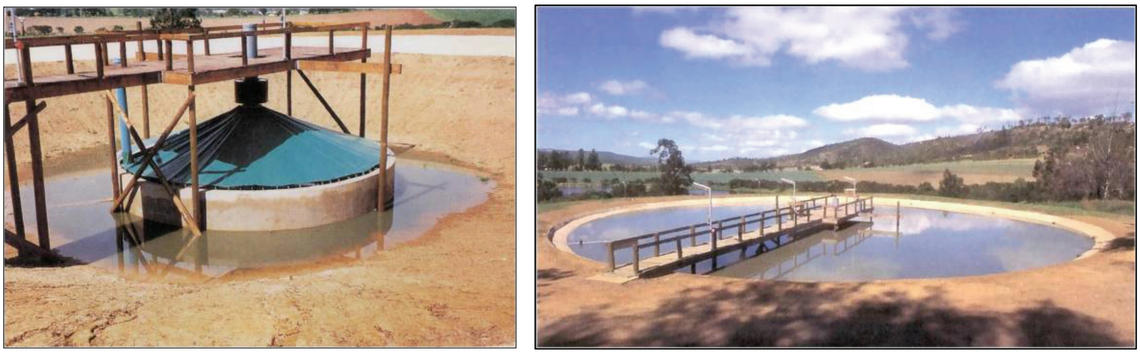


Figure 2.2: Primary Facultative Pond of the Integrated Algal Ponding System plant before filling, showing the fermentation pit, and after filling.

The PFP effluent enters the secondary pond, usually a HRAP (Figure 2.3). A HRAP is 30-40cm deep to ensure maximum light penetration and is mixed by a paddle-wheel to keep algae in suspension (Oswald, 1991) and decrease photoinhibition (Clark, 2002). Optimal flow rate was found to be about 20-30cm/sec (Clark, 2002). Microalgae produce large quantities of oxygen in the HRAP by photosynthesis which enable microbial breakdown of COD. Elevation of the pH of the water causes the stripping of ammonia and precipitation of phosphates as calcium phosphate (Clark, 2002). Nitrates are used in part of the algal growth and at night, when the dissolved oxygen (DO) level falls and ponds become anoxic, denitrification commences.

Figure 2.3: High-Rate Algal Ponds of the Integrated Algal Ponding System plant showing the paddle wheels and the flow path dividing walls.

Effluent then passes to Algal Settling Ponds (ASP) which are designed to allow gravitational sedimentation, and over 80% of the algae can be removed in this manner. Supernatant is released into the receiving water body. Algae from the ASP must be removed periodically and either utilised immediately or allowed to dry in drying beds (Figure 2.4).

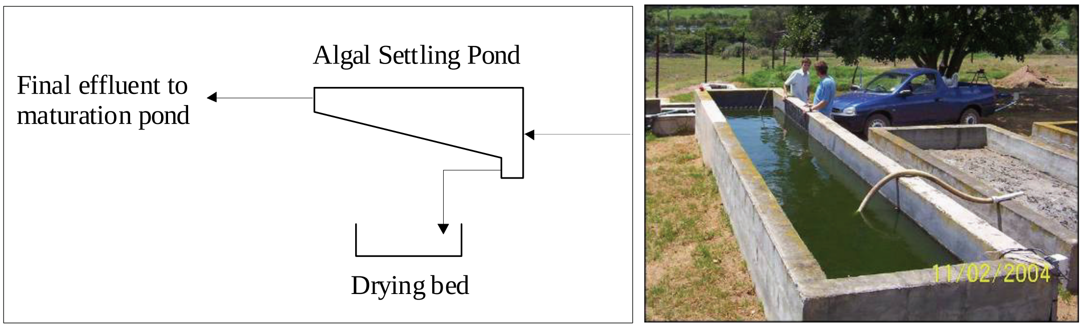


Figure 2.4: Algal Settling Ponds and Algal Drying Bed**.**

2.3 THE INDEPENDENT HIGH-RATE ALGAL POND AS A DISINFECTION OPERATION

Studies undertaken by Clarke (2002) showed that when two HRAP were run in series, a high level of disinfection was found to occur in the second pond. This lead to an investigation into the development of the HRAP as a stand-alone disinfection operation. These studies are reported by Wells & Rose (2006) and Wells (2005) and investigated nutrient removal rates, levels of disinfection as well as mechanisms behind the disinfection function observed in the IHRAP. It was demonstrated that the IHRAP could function as a free standing tertiary treatment unit operation (Figure 2.5) and could consistently produce water with faecal coliform counts of <1CFU.100ml^{-1} and *E. coli* counts of <1CFU.100ml^{-1} without the use of chlorine, ozone or any other sanitising chemical treatment. In addition to effective disinfection, ammonia and phosphate levels were also reduced to below discharge standards at 1.4mg.ℓ^{-1} and 2.3 mg.ℓ^{-1} respectively (Wells & Rose, 2006; Wells, 2005). A strong inverse correlation was observed between pH levels in the pond and nutrient removal and disinfection efficiency. It was thought that this relationship, coupled with high dissolved oxygen levels and sunlight penetration in the shallow ponds (±300mm) were involved in the mechanisms underpinning disinfection and pond efficiency (Wells & Rose, 2006).

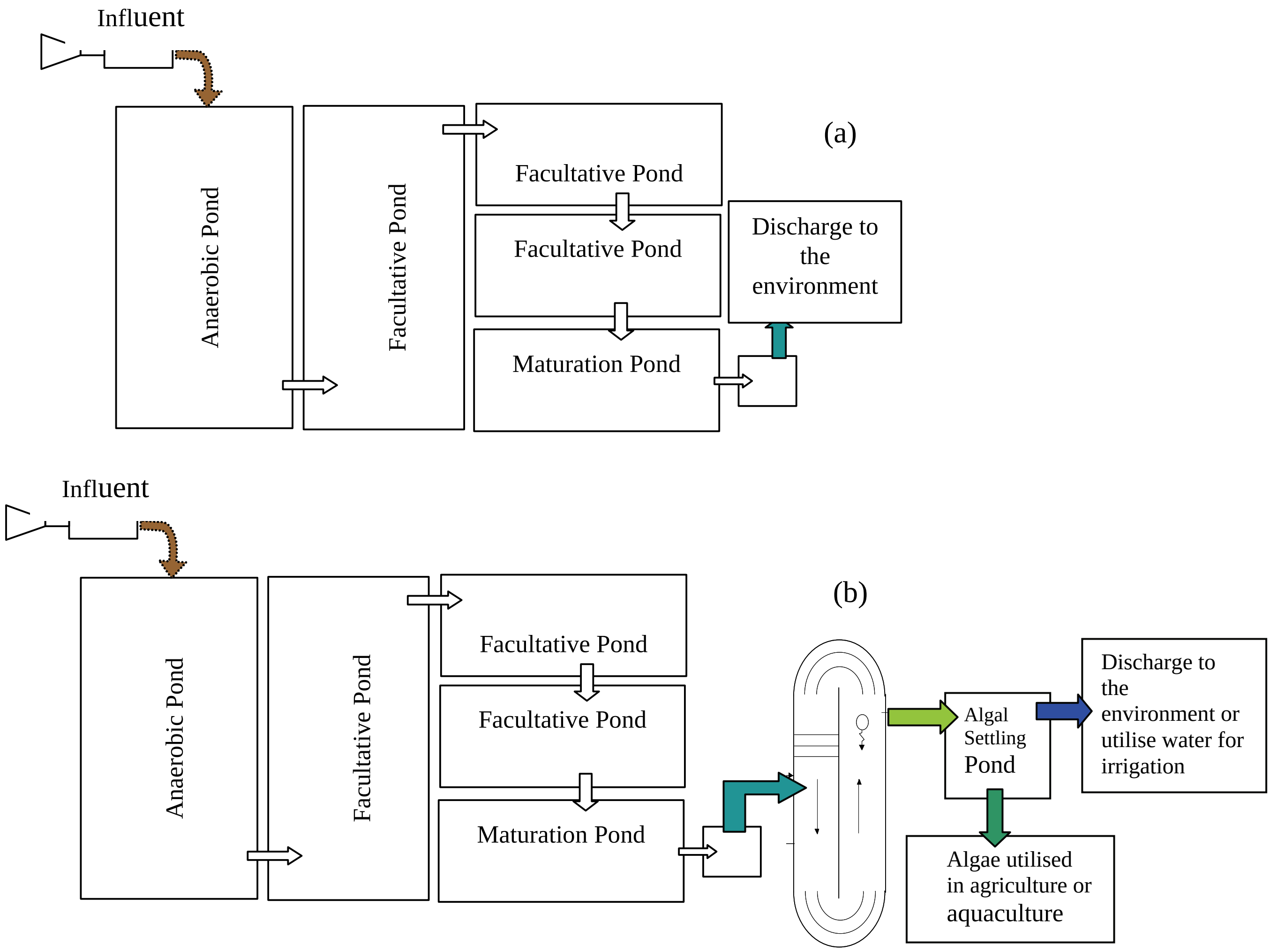


Figure 2.5: Typical sewage ponds (a) with an Independent High-Rate Algal Pond retrofitted as a polishing unit (b).

2.4 THE INDEPENDENT HIGH RATE ALGAL POND IN UPGRADING POORLY PERFORMING SEWAGE TREATMENT WORKS

A study on the status of municipal wastewater treatment in the Eastern Cape Province has shown that the threat to human and environmental health posed by inadequate wastewater treatment is widespread (Appendix I). This has been further confirmed as a country-wide problem by Snyman *et al* (2006). The two main conclusions arrived at in these studies are that disinfection using conventional chlorination techniques are not effective, due to operator skill--shortages, poor maintenance of infrastructure, as well as a lack of emphasis on disinfection as a key function of sewage treatment. It was also found that rapid urban development is increasing organic and hydraulic loading into sewage works which then need to be upgraded, usually at high cost, and, due to poor maintenance, infrastructural disrepair is widespread.

In addition to the absence of skills required to operate conventional systems such as trickle filters and activated sludge systems correctly, these systems also require a comparatively large amount of energy and extensive maintenance (Wells *et al*, 2006; Horan, 1996). Considering the above limitations of conventional domestic wastewater treatment services in the context of a rapidly developing country, it is appropriate to consider alternative technology types.

IAPS technology and the associated HRAP may be considered appropriate technology for the treatment of domestic and industrial wastewaters (Van Hille & Duncan, 1996; Rose *et al*., 1998). Apart from the ability of this technology to achieve and maintain the desired standard of treatment, it offers other advantages that should make it particularly applicable to users in developing countries. Algal ponding technology is relatively inexpensive in terms of both capital and operational costs (Brune *et al*., 2003). In gravity-fed systems, the only moving part would be the motorised paddle wheel of the HRAP, and thus the degree of mechanical maintenance and energy requirements of the system are extremely low. Furthermore, low operator skills are required due to the robust nature of the system,. The combined use of the IHRAP as a tertiary treatment unit operation and the recovery and reuse of the disinfected water and algae as an employment creating enterprise was the principal objective of the study that followed.

3 ALGAL BIOMASS RECOVER,Y AND ITS USE AS A FERTILISER: A REVIEW

3.1 AGRICULTURAL AND HORTICULTURAL USE OF ALGAL BIOMASS

The beneficial effects of algae on plant growth have been recognised by plant growers for centuries (Crouch and Van Staden, 1993a; Senn, 1987). It was not until the 1990s that researchers began to discover the possible reasons for these dramatic effects and some researchers considered "the precise mechanism by which they elicit their beneficial growth responses", as still not fully understood (Crouch and Van Staden, 1993a). The mineral content alone could not account for the magnitude of the results and authors have attributed this to naturally occurring plant growth regulators or plant hormones which occur in algae (Zhang and Schmit, 2000; Crouch and Van Staden, 1993a; Borowitska, 1988; Senn, 1987).

Plant hormones are the main internal factors controlling growth and development (Raven *et al*, 2004). Auxins are important plant hormones produced by growing stem tips, young leaves and in developing seeds and transported to other areas where it may either promote or inhibit growth. Auxins cause differentiation of vascular tissue and apical dominance in stems, whereas in roots it induces adventitious roots on cuttings while inhibiting growth in the main system. It inhibits leaf and fruit abscission while stimulating ethylene synthesis and fruit development. Ethylene is produced in most tissue in response to stress, especially in tissues undergoing senescence (maturation) or ripening, and promotes fruit ripening, leaf and flower senescence, and leaf and fruit abscission (Raven *et al*, 2004). Cytokinins are produced mainly in the root tips and promote cell division, shoot formation and growth of lateral buds (Raven *et al*, 2004). Gibberellins are produced in the young tissues of the shoot and developing seeds, possibly also in roots and are responsible for hyperelongation of shoots via cell division and induction of seed germination, stimulation of flowering in long-day plants and biennials, and regulation of production of seed enzymes in cereals (Raven *et al*, 2004).

Chelating agents are important as they determine the bioavailability of essential trace metals and nutrients. Organic acids such as citric acid, malonic acid and some amino acids, amongst other compounds act as chelating agents. Chelates are formed with organic acids, preventing precipitation of absorbed nutrients due to interaction with cationic nutrients upon entering plant cells,. This enables the nutrients to then move freely inside the plants. Natural chelating agents do not share the problems of the synthetics, and are state-of-the-art technology for delivering selected mineral and trace elements with maximum bioavailability, tolerability and safety (JH Biotech, Inc, 2005).

Senn (1987) established that brown seaweeds (Phaeophyta) contain cytokinins, gibberellins, and indoles which are natural plant growth regulators. Over 70 microelements and essential micronutrients are found in brown seaweeds e.g. iron, copper, zinc, molybdenum, boron, manganese, and cobalt, all necessary for healthy plant growth and development (Senn, 1987). It has also been reported that seaweed releases unavailable minerals from the soil and that these micronutrients serve as catalysts that activate enzymes (Senn, 1987). "Many seaweed products also contain a chelating carbohydrate, mannitol, that chelates micronutrients into complexes that are readily available for plant use," (Senn, 1987). Other studies to date have concentrated on specific chemical extracts produced from seaweeds (Nardi *et al*, 2004; Zhang and Ervin, 2004; Zhang and Schmit, 2000). A study by Zhang and Schmit (2000) describes seaweed extract as an exogenous hormone-containing that was tested on tall fescue (*Festuca arundinacea* Schreb.) and creeping bentgrass (*Agrostis palustris* Huds. A.). They claimed improved growth and a contribution to increased antioxidant concentrations.

Borowitska (1988) examined micro-algal extracts, also known to stimulate the growth of plants and attributes this, at least in part, to the presence of auxins, gibberellins, cytokinins and other hormones as does Shaaban (2001) in a study on the freshwater green alga *Chlorella vulgaris*. El-Fouly *et al* (1997) also make mention of the existence of chelating agents in *C. vulgaris* which when extracted and applied as a foliar feed facilitates penetration of elements through leaves. Micro-algae are also able to produce most vitamins depending on species, stage of growth, nutritional status and photosynthetic rate, as well as the "natural ethylene-releasing chemical 1-aminocyclopropane-1-carboxylic acid, which may be responsible for some of the growth stimulating effect of algal extracts," (Borowitska, 1988). At that time (1988), the possible application of micro-algal extracts in horticulture and agriculture had not been explored although the use of the algal biomass for 'green manuring' or as biofertiliser had been considered (Borowitska, 1988). It appears that most research in the field of growth promoters has remained focused on macroalgae or seaweed, on the promotion of blue-green algae in the rice paddies of India and China or *in situ* soil algae (Metting, 1988). More recent studies by Mulbry *et al* (2004, 2005) investigated the use of dried algae recovered from dairy wastewaters as an alternative to land application of animal manures. Algae was utilised to treat dairy wastewaters via an algal turf scrubber (ATS™), mechanically harvested after a period of 1-2 weeks and then dried (Craggs *et al*, 1996; Mulbry *et al*, 2005). The ATS is described by Craggs *et al* (1996) as "a natural, mixed assemblage of attached periphyton, microalgae and bacteria which colonised an inclined floway 152 m long and 6.7 m wide, over which wastewater flowed in a series of pulses." Initially Wilkie and Mulbry (2002) and Mulbry *et al* (2004) considered the algal biomass as an alternative protein feed for animals, but recognised the potential of the biomass as a valuable organic fertiliser. The algal biomass was shown to have balanced N:P ratio (Mulbry *et al*, 2004) which made it ideal as an organic fertiliser. Field trials showed that seedlings grown in harvested and dried ATS biomass amended potting mixes "were equivalent to those grown with comparable levels of fertiliser with respect to seedling dry weight and nutrient content" (Mulbry *et al*, 2005). The dried algae was found to have the advantage of acting as a slow-release fertiliser (Mulbry *et al*, 2005) but no mention was made of the well known added benefit of the additional organic matter as mulch, or the potential benefits of growth-stimulating plant auxins from the algal biomass as suggested by Borowitska (1988).

It has been shown that seaweeds increase respiratory activity and germination percentage of the seeds of zinnia, tobacco, peas, turnips, tomato, radish, cotton, white pine, loblolly pine, Ligustrum, nandina, and American holly (Senn, 1987). Senn (1987) conducted numerous experiments as briefly outlined below. Seaweed extract was evaluated as a pre-germinating medium for onion seeds and was found to increase germination as well as consistent radical length. The same experiment on beet seed increased germination by between 25% and 84% over the control, depending on treatment time. This was done using seaweed extract at concentrations between 1-25 and 1-50 parts water. Senn (1987) attributes these results to the many gibberellins and cytokinins contained in brown seaweed. Young (in Senn, 1987) studied the effect of seaweed extract on the roots of plants and found that seaweed extracts used as regular foliar sprays and soil feeds encouraged root development in a range of crops including wheat, sunflowers, beans, corn, peas and grasses and reports that other plant studies have produced similar results. Again Senn (1987) attributes these results to the presence of cytokinins as these can affect nutrient uptake into the roots of plants. Accelerated uptake of nitrates, phosphorus, potassium and calcium into the plant roots were attributed to the presence of cytokinins. Regular applications speeded up the healing of cut surfaces and induced the development of a large number of roots. In an earlier study by Featonby-Smith and Van Staden (1983), similar results were observed where application of seaweed concentrate (SWC) significantly improved root growth in tomato plants. Further studies into the effects of SWCs were conducted by Atzmon and Van Staden (1994) which found that applications of SWC as 'root drenches' did not change the total weight of pine seedlings (Pinus pinea) but was shown to accelerated root growth and increased lateral root dry weight. Tests for both shoot and root applications indicated an increase in root length and some increases in root number when applied as a root drench (Atzmon and Van Staden, 1994). SWC are also widely used in Europe for tree and shrub transplanting with great success (Senn, 1987).

Senn (1987) recommends the use of SWC for increasing the health of crop plants reaching maturity or harvest-readiness as well as an increased 'fruit set' and maintains that SWC delays senescence in plant organs, prolongs shelf life of various fruits and vegetables for as much as 2 to 3 weeks. When SWC was sprayed onto grapevines at bud burst and subsequent treatment with SWC as a foliar feed an increase in fruit production, particularly under adverse climatic conditions, was observed (Senn, 1987) Increased insect and disease resistance and particularly to nematodes were other properties observed in plants sprayed with SWC (Crouch and Van Staden, 1993b; Senn, 1987; Featonby-Smith and Van Staden, 1983) with one experiment showing 98% reduction in the population of *Paratylenchus spp*. pin nematodes; and 48% reduction in *Fusarium roseum* on Kentucky Bluegrass turf (Senn, 1987). In addition, seaweed extract applied as a foliar spray on apples appeared to suppress the reproduction rates of mites (Senn, 1987). Both popular and scientific literature report resistance to fungal diseases by plants treated with seaweed extracts. Senn (1987) noted that powdery mildew on leaves on cantaloupe (spanspek) plants could be reduced by application of SWC.

Senn (1987) reports on the effects of growth regulators on stress resistance and particularly the plant's ability to withstand changes in temperature and drought conditions by aiding changes in the metabolic pathways thereby permitting the roots access of extremely low moisture levels not normally available to plants. This was substantiated by preliminary field trials on dry land cereal crops in Canada by Dr Wayne Temple (in Senn, 1987). Besides adding organic content to soils, widely accepted to increase the water holding capacity of soils, seaweeds contain alginates that improve water-holding capacities (Senn, 1987). The large number of micronutrients also acts as fertiliser, to correct soil nutrient deficiencies, as well as increase the formation of humus (Senn, 1987). Further research by Zhang and Ervin

(2004) proved that seaweed extracts containing cytokinins increased the drought resistance in creeping bentgrass (*Agrostis palustris* Huds. A.).

Many studies have been conducted into the yield and quality of crops treated with SWC as a foliar spray and as a soil application (Atzmon and Van Staden, 1994; Crouch and Van Staden, 1993a&b; Senn, 1987; Featonby-Smith and Van Staden, 1983). Positive results were obtained for yields of potatoes, lettuce, cauliflower, tomatoes, citrus, sweet potatoes, apples, strawberries, cucumbers and clover. Apricots, cherries, peaches, and plums showed increases in both quality and quantity of fruit (Senn, 1987). Experiments by Senn (1987) into cut flower production (long stem roses) achieved a 32% increase and cotton yielded up to 29% due to increase boll number per unit area. Foliar applications of SWC on Swiss chard "significantly improved the growth irrespective of whether it was applied on its own as a foliar spray or together with soil applications of a chemical fertiliser."

Commercially available products utilising algae as fertiliser and foliar feeds generally appear to be using seaweed which is marketed as an organic alternative to conventional inorganic or chemical fertilisers. A well-known brand in South Africa utilises kelp (Ecklonia maxima) in the manufacture of foliar feeds and other products (Kelpak, 2005). The products were developed based on doctoral research by B.C Featonby-Smith and I.J. Crouch, as well as a number of studies done by these authors together with J. van Staden and others (Kelpak, 2005). Manufacturers' claims agree with those of the scientific research outlined above. Products are "....packed with minerals, vitamins, amino acids and natural growth hormones. Seaweed is exceptionally beneficial to plant life. It provides essential nutrients while simultaneously improving the soil structure and increasing its water-holding capacity. It aids in frost protection and helps plants ward off fungal, insect and worm infestations. Its organic composition enables [the seaweed fertiliser] to act as both a year round slow release fertiliser and soil conditioner, ensuring that plants receive even quantities of nutrients over a period of time. As the decomposition of seaweed is much simpler than land plants, [the seaweed fertiliser] aids in the formation of humus, stimulating earthworm and microbial activity and improving the structure of the soil." (SeaGro Superkel pamphlet, 2004). Another manufacturer emphasises the role of the "growth bio-stimulants" and added value of "soil conditioners". Yet another claims the presence of "Algae polyose and polyphenols … can remarkably promote the growth of plants and roots development, enhance photosynthesis, strengthen stalks, and increase the plants' ability to resist disease, pests, coldness and draught, improve quality, stimulate the maturity of fruitage, ameliorate the soil texture and preservation of soil moisture".

3.2 CONCLUSIONS

The following conclusions may be drawn from the above review:

1. The literature reveals considerable potential in the use of macro- and microalgae in a wide range of horticultural applications
2. The growth stimulating properties of algae, while well known for seaweeds, is relatively unexplored for microalgae such as that grown in the IAPS and the IHRAP
3. Potential applications of algal biomass range from simple soil amendment to the

manufacture of growth stimulating foliar feeds on a commercial scale. Thus the use of the IAPS to recycle nutrients and water for downstream horticultural applications has the potential to change the paradigm of wastewater treatment from service provision, where costs are covered from rates and taxes, to a business unit which turns sewage into a commercial resource.

This practical approach underpins the research into the use of the algae as it has the potential to change the way we regard nutrients in wastewater, and simultaneously mitigate financial, social and environmental problems relating to sustainability in wastewater treatment.

4 UNICELLULAR ALGAL BIOMASS AS A FERTILISER: LABORATORY STUDIES

4.1 INTRODUCTION

A primary aim of the Water Research Commission Project K5/1619 was to determine the horticultural or agricultural value of algal biomass produced by the IAPS as a key strategy in developing and marketing the system as not only a low-cost sanitation technology, but one that offers opportunities for resource recapture, and is therefore also sustainable. In order to ascertain the value of the algal biomass in this context, soil amendment trials were conducted utilising the algae in its raw harvested state, and secondly after some processing as a foliar feed, for the improvement of crop yields.

4.2 EXPERIMENTAL METHODOLOGY

,The experiment was undertaken in a horticultural tunnel (Figure 4.1) in order to create a controlled environment The tunnel was set up with a computer-controlled drip irrigation system, which delivered 2ℓ/minute per dripper at 1bar supply pressure, to ensure that all plants received equal amounts of water. The plants were irrigated at regular intervals using municipal water, determined initially on a basis of keeping soil moist, and subsequently programmed to provide small amounts of water at set times during each day. All plants were planted in soil-filled plant bags. Tunnel temperatures were monitored but not controlled.

Figure 4.1. The horticultural tunnel at the Environmental Biotechnology Research Unit field station in which pot-trial studies were conducted.

4.3 SOIL AMENDMENT TRIALS

4.3.1 First Season Soil Amendment Trials

Swiss chard (*Beta vulgaris* L.cicla) and Radishes (*Raphanus sativas*) were planted in plant bags in the tunnel. Swiss chard was selected as a leaf crop, which could be harvested repeatedly. Radishes were selected due to the short planting-to-harvest period.

The soil used was obtained from a nearby site and was prepared by sifting and mixing, so as to ensure consistency throughout all experiments. Eight rows were set up for soil amendment trials and three remaining rows for foliar fertilisation trials.

Approximately 27 repetitions of each experimental condition for each plant were created as follows:

1 A control with no treatments (C)
2 1st treatment - Commercial inorganic fertiliser, N:P:K 2:3:2 (F)
3 2nd treatment - Algal biomass applied as a slurry (A)
4 3rd treatment - A combination of algal biomass and inorganic fertiliser (AF)

The nitrogen content of the harvested algae was assayed and compared with algal nitrogen content arising from use of commercial inorganic fertiliser. Kjeldahl nitrogen assay of the harvested and dried algal biomass, as well as the inorganic fertiliser, was performed. Using these results, all treatment quantities were then calculated on the basis of providing plants with identical quantities of added "treatment" nitrogen, to enable growth-rate comparisons to be made on a basis of an equal quantity of added nitrogen. 2:3:2 application rates were based on the average recommended fertilisation rates for the two chosen crops at 100g 2:3:2 m^3 (Gilbertand Hadfield, 1996). The quantity of fertiliser required per bag was then calculated using the surface area of the plant bags. This amounted to 1.54 g/plant bag of 2:3:2 fertiliser for the fertiliser treatments and 0.77 g/plant bag of 2:3:2 fertiliser for the fertiliser-algae treatments. Swiss chard seedlings were purchased from a local nursery and planted out (Figure 4.2). Radish seed was planted directly into plant bags. Seventeen days after planting, radish seedlings were thinned out to one radish plant per plant bag. The radishes were harvested after 5 weeks.

Half of Swiss chard replicates were re-fertilised at the same rate as the first application after 11 weeks. All plants were harvested after 16 weeks. This then gave 6 treatments and the control, i.e.

1 The control with no treatments (C) – remained the same
2 1st treatment - Inorganic fertiliser, one application (F1)
3 2nd treatment - Algal biomass applied as a slurry, one application (A1)
4 3rd treatment - A combination of algal biomass and inorganic fertiliser, one application (AF1)
5 4th treatment - Inorganic fertiliser, two applications (F2)
6 5th treatment - Algal biomass applied as a slurry, two applications (A2)
7 6th treatment - A combination of algal biomass and inorganic fertiliser, two applications (AF2)

The whole plant weight, root weight, diameter, and root length of radishes were measured. Leaves of Swiss chard were weighed. Both Swiss chard and radishes were weighed for fresh (wet) weight, oven-dried weight and ash-free dry weight. Results of the fresh weight results are reported below.

Figure 4.2: Swiss chard and radishes growing in plant bags in the pot trials

4.3.2 Second Season Soil Amendment Trials

The main aim of the second season of soil amendment trials was to determine the longer term effects of the different treatments on nutrient availability and growth rates, and to test the hypothesis that algal biomass releases nutrients into the soil slowly or continues acting as a slow-release chelating agent, and therefore makes nutrients available to the plants over a longer period than the inorganic fertiliser 2:3:2. As with the first season, the experiment was undertaken in the horticultural tunnel with computer-controlled drip irrigation in order to create a controlled environment. Again Swiss chard (*Beta vulgaris* L.cicla) and radishes (*Raphanus sativas*) were used as experimental plants, due to their differing nutrient requirements, growth season and ease of cultivation (Figure 4.3). Besides the above reasons, radishes were chosen, as they are widely used in agronomic studies due to their rapid growth rate (5 weeks to maturity). Two crops of radishes were grown in the second season. Swiss chard was already established in the first season and could thus be harvested a second time in the second season to determine long-term effects of the different treatments over two seasons. As with the previous season, 8 rows were set out for the soil amendment trials with 27 or 28 replicates for each experimental condition and set up as follows:

1. A control with no treatments (C)
2. 1st treatment - Inorganic fertiliser (F)
3. 2nd treatment - Algal biomass applied as a slurry (A)
4. 3rd treatment - A combination of algal biomass and inorganic fertiliser (AF)

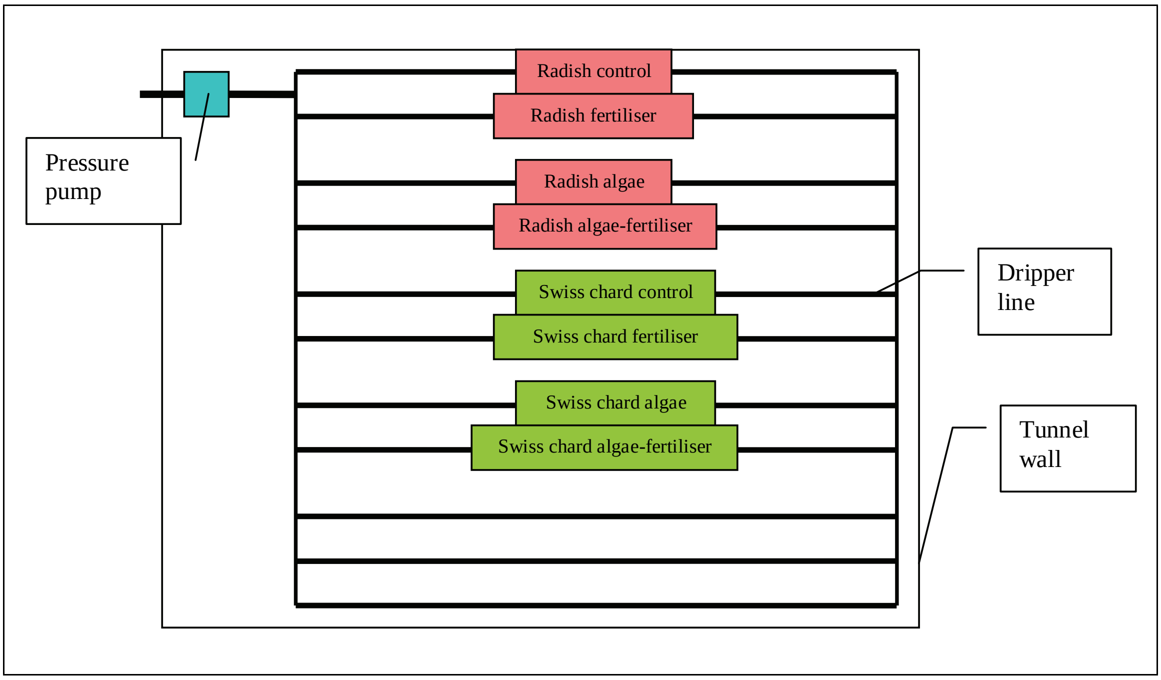


Figure 4.3. Tunnel layout for second season**.**

The same soil was used in the second season trials as for the first experiment and no additional inorganic fertiliser or algal biomass was added. The methodology for the second season's radish harvest was as used for the first season. Two crops of radishes were planted and harvested consecutively in the second season. The second and third radish crops were harvested 5 weeks after planting, washed, dried, weighed and measured as before. Fresh weights were measured for the entire plant and then the root portion only, to derive leaf to root ratios as well as crop yield. A sub-sample of 10 radishes was dried at 100°C overnight to measure oven-dried weights and then ashed in a furnace at 600°C for 4 hours to obtain residual ash content. The difference in the two results has been termed the ash-free oven-dried weight.

After the second growth season, it was decided to measure the whole biomass of the Swiss chard including roots and shoots. Plant bags were removed and soil washed from the roots. The entire plants were then air-dried to remove excess moisture and this weight measured as "wet weight". Roots were removed and weighed separately from shoots. Shoot height was also measured. A sub-sample of 10 plants (roots and shots) was dried at 100°C overnight to determine oven-dry weights, and then combusted in a furnace at 600°C for 4 hours to determine ash content. Ash-free oven-dried weight was calculated, as before.

4.3.3 Third Season Soil Amendment Trials

Virgin soil was dug out on-site and plant bags filled. Fresh algal biomass, inorganic fertiliser and algal fertiliser amendments were added according to recommended nitrogen application rates (Gilbert and Hadfield, 1996) as in the first season. Kjeldahl nitrogen analysis (APHA, 1998) was conducted to determine total nitrogen content of the algal biomass and therefore the application rate. Twelve replicates were used for each treatment and for the control. Radishes were planted directly into the soil from seed. Many seeds did not germinate and a second planting was necessary. The radish crop was harvested 5 weeks after planting, washed, dried, weighed and measured. Fresh weights were required for the entire plant as well as the root portion only, to derive leaf-to-root ratios as well as crop yield. A sub-sample of 5 radishes for each treatment was dried at 100°C overnight to measure oven-dry weights and then ashed as before, giving results from which the ash-free oven-dried weight could be calculated.

4.3.4 Statistics

Statistical analysis was carried out using the Statistica 7™ package. Normality tests were performed and if a data set was found to be normal, one-way analyses of variance (ANOVA) were conducted to determine if there was a significant difference between treatments. Levene's test was carried out to determine homogeneity of variance between treatments. These were followed by a post-hoc Sheffé test to show which treatments were significantly different from each other. If a data set was not normal, a Kruskal-Wallis nonparametric ANOVA was conducted, followed by a Multiple Comparisons (2-tailed) test to show which treatments differ significantly t from the others.

4.4 RESULTS AND DISCUSSION

4.4.1 Radishes: First Harvest

Average fresh root weights of the first radish harvest showed 2:3:2 (F) to have the highest yield (Figure 4.4) followed by algae+2:3:2 (AF) and then algae (A). Statistical analysis showed that the difference between the control (C) and the other treatments was highly significant ($p<0.001$) but not between treatments A, AF and F (Table 4.1). Data on whole plant weight and root weight of radishes, data indicate that F and AF promote a higher proportion of leaf growth and statistically, that algae performed equally with the 2:3:2 and the algae+2:3:2 combination. Similarly, the results of analysis on oven-dry weights show that, again the control was significantly different from the treatments (Table 4.1). It may be observed that the addition of algae or the algal+2:3:2 combination produces crop yields that are statistically equivalent to that of the 2:3:2 applied at the recommended rate.

Table 4.1: Scheffe post hoc test showing which treatments are significantly different in radish root weight and root dry weight results. (S = significant; ns = not significant)

Treatment	**C**	**F**	**A**	**AF**
C	/	s	s	s
F	s	/	ns	ns
A	s	ns	/	ns
AF	s	ns	ns	/

When the ash-free dry weights are used, however, no significant difference between A and C is observable, but significant differences occur for all other permutations (Table 4.2).

Table 4.2: Scheffe post hoc test showing which treatments are significantly different in radish root ash-free dry weight results.

Treatment	**C**	**F**	**A**	**AF**
C	/	s	ns	s
F	s	/	s	s
A	ns	s	/	ns
AF	s	s	ns	/

4.4.2 Radishes: Second Harvest

Average fresh root weights of the second radish harvest showed that 2:3:2 again produces the heaviest root weights (Figure 4.4) but yield of AF and F performs equally and with only 1g difference in average weight between F and the other two treatments (AF and A). As with the first harvest, statistical analysis shows that the significant difference ($p<0.05$) between treatments occurs between the Control (C) and the other treatments, but not between Treatments A, AF and F (Table 4.3). Dry weights have the same pattern of significant differences as the fresh root weight (Table 4.3). Again there is a statistically significant difference between crop yields of 2:3:2, A and AF.

Table 4.3: Scheffe post hoc test showing which treatments are significantly different in radish fresh and dry weight results.

Treatment	**C**	**F**	**A**	**AF**
C	/	s	ns	s
F	s	/	ns	ns
A	ns	ns	/	ns
AF	s	ns	ns	/

The ash-free dry weights showed significant differences between the control and the three treatments (Table 4.4).

Table 4.4: Scheffe post hoc test showing which treatments are significantly different in radish ash-free dry weight results.

Treatment	**C**	**F**	**A**	**AF**
C	/	s	s	s
F	s	/	ns	ns
A	s	ns	/	ns
AF	s	ns	ns	/

4.4.3 Radishes: Third Harvest

The pattern of performance changs for the third harvest (Figure 4.4) with AF producing the highest average fresh root weights followed closely by F. Treatment A still has some growth stimulating properties, however, this was is significantly different ($p>0.05$) from the performance of C (Table 4.5) and also not significantly different to AF or F. As before, AF and F are significantly different from C ($p<0.05$). The overall higher yield for treatments and control can be attributed to a generally higher growth rate over the 5 weeks, due to increase in day length and temperatures of summer.

Table 4.5: Scheffe post hoc test showing which treatments are significantly different in radish root weight and dry weight results.

Treatment	**C**	**F**	**A**	**AF**
C	/	s	ns	s
F	s	/	ns	ns
A	ns	ns	/	ns
AF	s	ns	ns	/

It is interesting that ash-free dry weights are different, with a significant difference ($p<0.05$) occurring between AF, F and A and C (Table 4.6).

Table 4.6: Scheffe post hoc test showing which treatments are significantly different in radish ash-free dry weights results.

Treatment	C	F	A	AF
C	/	s	s	s
F	s	/	ns	ns
A	s	ns	/	ns
AF	s	s	s	/

Statistical analyses for all harvests show that patterns for fresh whole weights, root diameter and length were similar to root weights and this is reflected in the graph of average measurements per harvest (Figure 4.5).

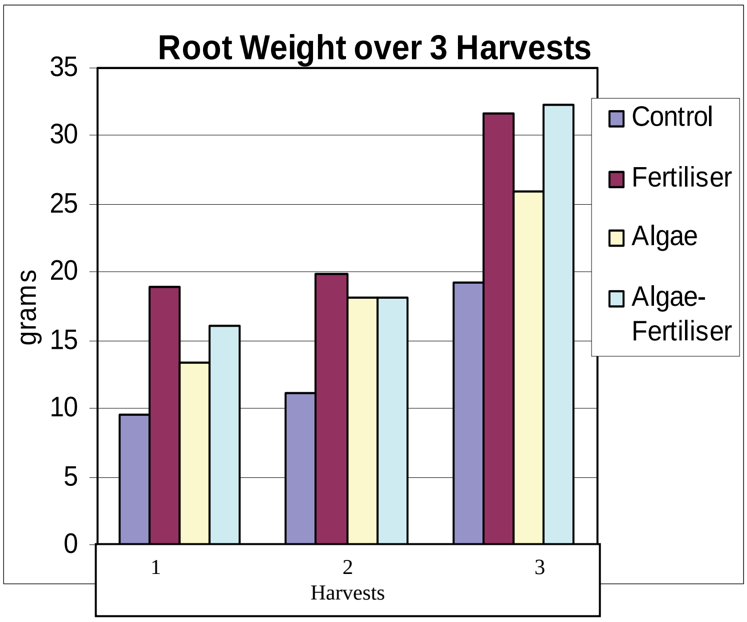


Figure 4.4. The root mass of the first, second and third harvests illustrate the change of yield over time for the different treatments.

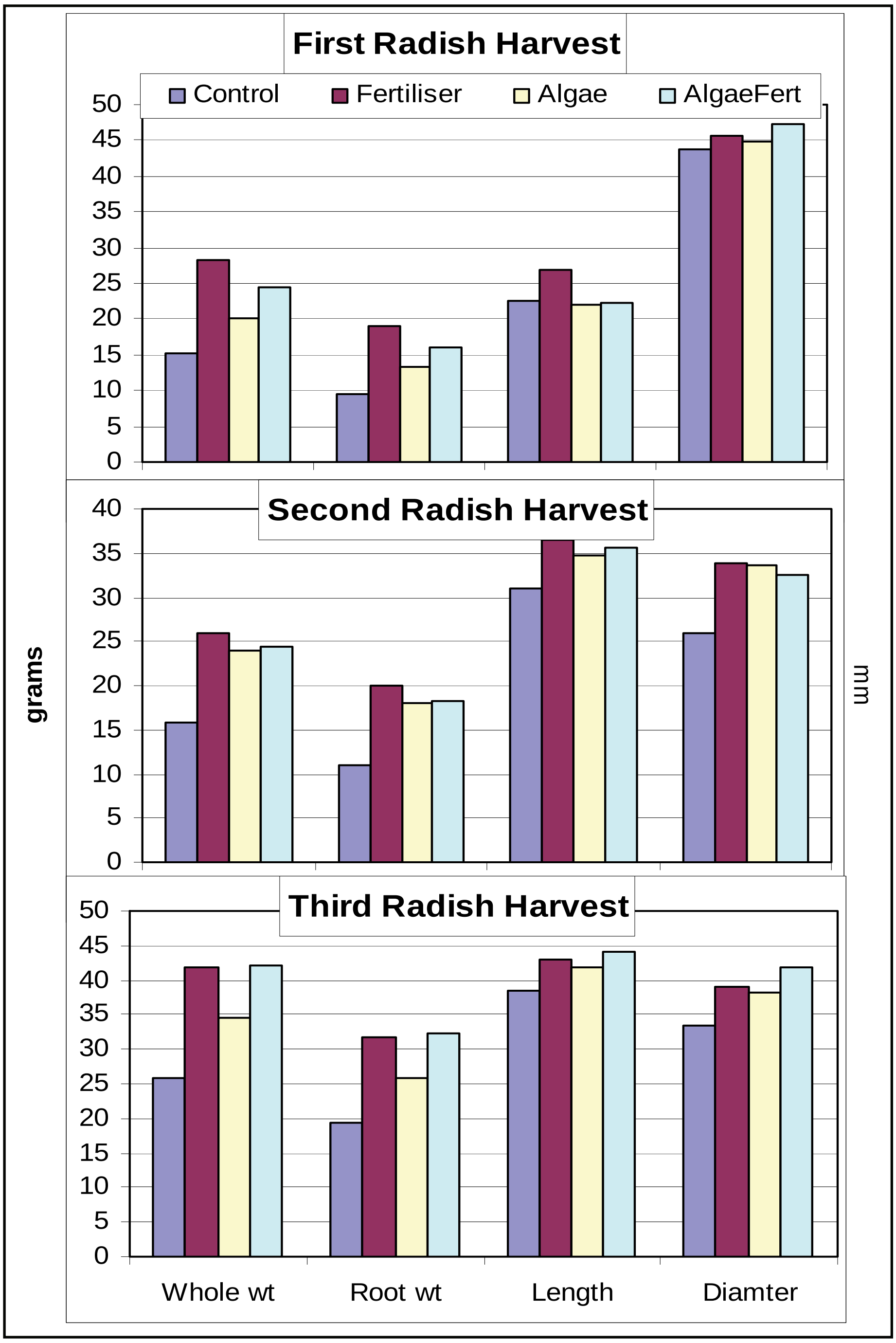


Figure 4.5: Harvest results for radishes over three harvest periods showing a change in relative growth rates over time

Three radish crops planted consecutively in the same soil with no further amendment show that algal biomass sourced from the IHRAP as a soil amendment as well as used in combination with 2:3:2 consistently produces radish yields statistically comparable to crop yield when 2:3:2 is used, both in the short-term (1 crop) and the longer-term (3 crops).

4.4.4 Radishes: Fourth Harvest

The fourth run of soil amendment trials for radishes produces results similar to the previous three trials (Figure 4.6) where algal biomass significantly increases yield and performs as well as 2:3:2. Algal biomass harvested from the IHRAP and applied directly to the soil before planting is found to significantly increase yield in radishes. One key difference in the fourth experimental trial run is that the average plant and root mass is higher where algal biomass has been used as a soil amendment in comparison to 2:3:2. Again, the algae+2:3:2 combination shows lower yields which confirmed results from previous trials, and suggest some initial inhibition in yield when algal biomass is used in combination with inorganic fertilisers for soil amendment. The results may indicate that where soil exhaustion arises, algal amendment may perform better than inorganic fertilisers.

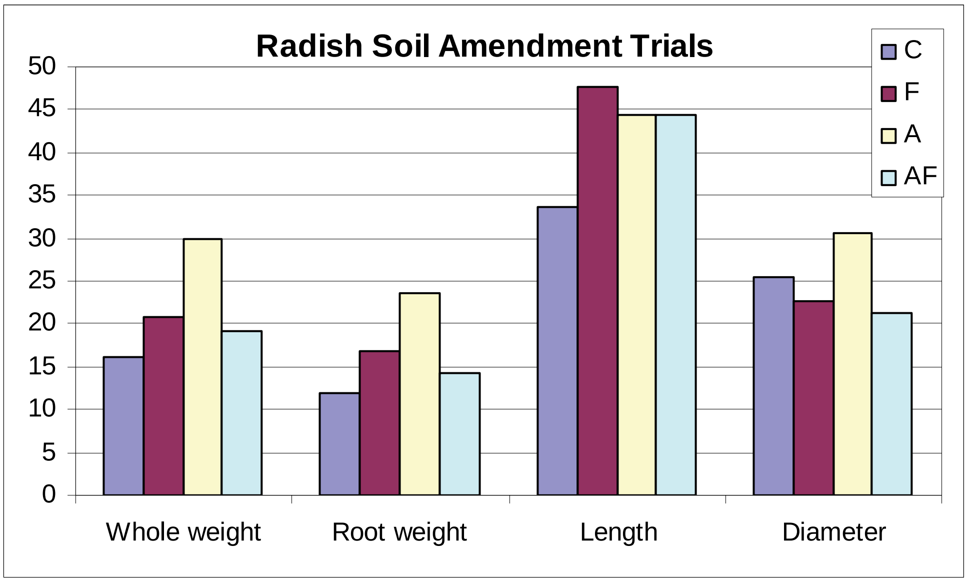


Figure 4.6: Results from soil amendment trials showed that algal biomass produced highest harvest weights but some inhibition was caused when combined with fertiliser.

A second planting of radishes was necessitated where the poor quality or age of the seeds used in the first planting resulted in poor germination. This has resulted in two age cohorts (visible in size variance in Figure 4.6) and the complication of statistical analyses. Although Figure 4.6 reflects similar trends to the previous three soil amendment trials, differences cannot be verified as statistically significant.

4.4.5 Swiss Chard: First Harvest

For the Swiss chard which received a single application of soil amendment, analyses of the harvestable crop weight data show a significant difference between treatments ($p<0.001$). The Scheffe's Post-hoc test shows that the control is significantly different from all other treatments. A, F and AF are not significantly different from one another (Table 4.7).

Table 4.7: Scheffe post hoc test showing which treatments are significantly different in swiss chard dry weight results.

Treatment	**C**	**F**	**A**	**AF**
C	/	**s**	**s**	**s**
F	**s**	/	ns	ns
A	**s**	ns	/	ns
AF	**s**	ns	ns	/

Similarly, for the Swiss chard which received two applications of soil amendment, analyses of the harvestable crop weight data show a highly significant difference between treatments ($p<0.001$). Scheffe's Post-hoc test (Table 4.8) shows that the control is significantly different from all other treatments, except AF1. This is contrary to the previous findings, and further experiments are needed to investigate this anomaly. AF1 is significantly different from F2, A2 and AF2. These results indicate that in most cases, additional nutrients supplied by a second application of the soil treatments does not significantly increase growth, and nutrients are therefore not a limiting factor in plant growth.

Table 4.8: Scheffe post hoc test showing which treatments are significantly different in swiss chard dry weight results.

Treatment	**C**	**F1**	**F2**	**A1**	**A2**	**AF1**	**AF2**
C	/	**s**	**s**	**s**	**s**	ns	**s**
F1	**s**	/	ns	ns	ns	ns	ns
F2	**s**	ns	/	ns	ns	s	ns
A1	**s**	ns	ns	/	ns	ns	ns
A2	**s**	ns	ns		/	**s**	ns
AF1	ns	ns	**s**	ns	**s**	/	**s**
AF2	**s**	ns	ns	ns	ns	**s**	/

1 C: Control

2 F1: 2:3:2, one application

3 F2: 2:3:2, two applications

4 A1: Algal biomass applied as a slurry, one application

5 A2: Algal biomass applied as a slurry, two applications

6 AF1: A combination of algal biomass and 2:3:2, one application

7 AF2: A combination of algal biomass and 2:3:2, two applications

4.4.6 Swiss Chard: Second Harvest

The second season harvest revealed no significant differences between the plants treated once versus those which received two treatments. All results are, therefore, shown as for four treatments.

Destructive sampling was conducted in order to ascertain if root growth was significantly different among treatments. Whole weights, root and shoot weights as well as shoot heights were measured with different patterns of growth stimulation in comparison to the radishes. Figure 4.7 shows that plants which grew in soil treated with algal biomass outperform all other treatments for all parameters measured.

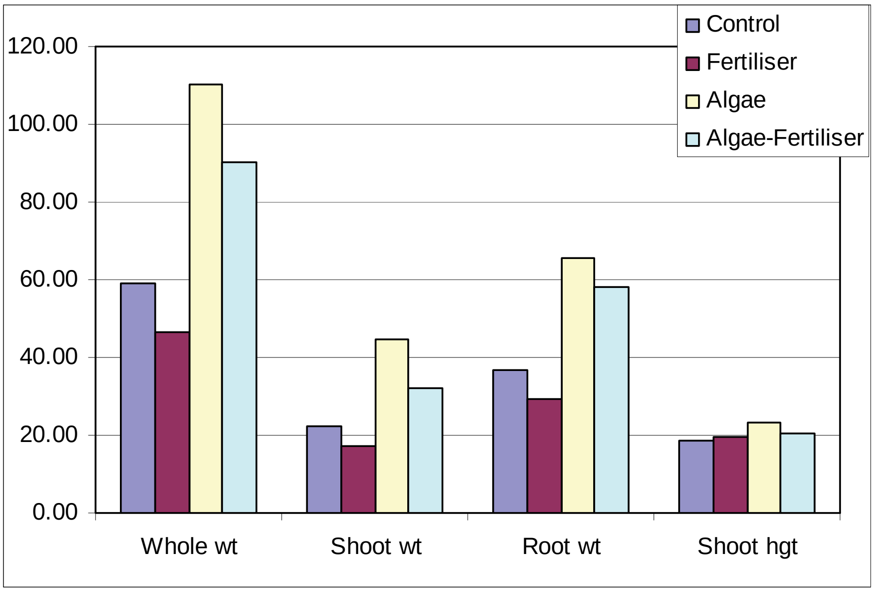


Figure 4.7: Final harvest results showing that algal treatment outperformed all other treatments for Swiss chard growth.

Statistical analysis shows that these differences are highly significant ($p<0.001$) for all aspects. Algal biomass as a soil amendment significantly increases whole, shoot and root weight of Swiss chard in comparison to the control, 2:3:2, and an algae+2:3:2 combination. The algae+2:3:2 combination also significantly improves growth in comparison to the control and the fertiliser, but weights are still significantly less than in the algal treatments (Table 4.9).

Table 4.9. Swiss chard final harvest: Whole weight; Shoot weight; Root weight ($p<0.001$)

Treatment	**C**	**F**	**A**	**AF**
C	/	ns	**s**	**s**
F	ns	/	**s**	**s**
A	**s**	**s**	/	**s**
AF	**s**	**s**	**s**	/

Algal biomass significantly improves the shoot height compared to C and F but not AF, and AF is significantly different from the C and F (Table 4.10). 2:3:2 was consistently the poorest performer of the three treatments, and does not show a significant effect on growth for any of the measured parameters.

Table 4.10. Swiss chard final harvest: Shoot height ($p<0.001$)

Treatment	**C**	**F**	**A**	**AF**
C	/	ns	**s**	ns
F	ns	/	**s**	ns
A	**s**	**s**	/	ns
AF	ns	ns	ns	/

The purpose of using a leaf crop and a root crop was to examine the effect of algal biomass as a soil feed on root versus shoot development. Statistical analyses show that differences in root weights among treatments display the same patterns of differences in shoot weights.

Although the results of the radish harvest and the Swiss chard harvest do not correlate exactly, the trend in both show that algae can be used as an alternative to 2:3:2 without compromising, but even improving on crop yield. It is an indication that two primary mechanisms are responsible in the growth stimulation by algae when applied directly to soil as an amendment. Algal biomass was applied to soil as a slurry in which some nutrient may have been immediately available to the plant in initial phases of growth, similar to the 2:3:2. These quantities would have been relatively small, as the algal quantities have been based on the equivalent total nutrient value of the liquid and biomass of the slurry. However, as the yields from plants receiving the algal soil amendment are not significantly different from the yields of those receiving 2:3:2, it is possible that other factors are responsible for the good yields over the short term (first harvests of radishes and Swiss chard). Algae can contain chelating agents (El-Fouly *et al*, 1997; Ahner *et al*, 1995) thereby increasing bioavailability of nutrients already present in the soil, as well as act as a soil conditioner, organic matter is added as algal biomass. Zhang (1997) however showed that although enhanced plant growth with seaweed application was initially attributed to its soil-conditioning properties, increased trace element supply alone could not explain all of the beneficial effects of seaweed. Senn (1987) attributes these results to the presence of cytokinins as these can affect nutrient uptake into the roots of plants. Accelerated uptake of nitrates, phosphorus, potassium and calcium into the plant roots has been attributed to the presence of cytokinins. Similar studies agree that the mineral content alone could not account for the magnitude of the results observed and have attributed this to naturally-occurring plant growth regulators or plant hormones in algae (Zhang and Schmit, 2000; Crouch and Van Staden, 1993a; Zhang, 1997; Borowitska, 1988; Senn, 1987). Although some researchers consider the exact mechanisms behind the beneficial growth responses as not fully understood, beneficial effects of algae on plant growth have been recognised by plant growers for centuries (Crouch and Van Staden, 1993a; Senn, 1987). Literature on use of algae in horticulture and agriculture emphasises the role of plant growth hormones such as cytokinins, auxins and gibberellins provided by algae for plant growth stimulation.

While the short-term effects of algal biomass as a soil feed can be attributed to presence of plant hormones in the algal exudate, as suggested in the literature (Zhang and Schmit, 2000; Crouch and Van Staden, 1993a; Zhang, 1997; Borowitska, 1988; Senn, 1987), long term plant growth stimulation may be due to the nutritional value of the algal biomass itself. Once algal biomass is removed from a growth environment, cells will die off and hormones will become depleted. Soil microbial activity will begin to break down biomass, thus releasing chemical constituents and nutrients into the soil, as well as promoting general soil health as humus via organic matter (Tilman *et al*, 2002). This cannot account for the long-term growth stimulation particularly evident in the results for the second harvest of Swiss chard which shows significantly higher yields for plants receiving algal treatment. Plants receiving 2:3:2 show a relative decrease in yield, while plants treated with a combination of algae and 2:3:2 perform better than 2:3:2 in the final yield, but not as well as the algal treatment (Table 4.9 and 4.10). This is a strong indicator that nutrients from the 2:3:2 have been depleted or are unavailable, in comparison to the first harvest and in comparison with the algae, resulting in poor growth over a period of 6 months.

4.5 CONCLUSIONS

, The following conclusions can be drawn from the laboratory-scale experiments:

1. Algal biomass produced from the IHRAP can be successfully harvested and used as a soil amendment
2. Radish yields are increased from an average <10g.plant^{-1} for untreated soil to 13g.plant^{-1} for soil that has been treated with algal biomass, and are statistically comparable with the average weight of radishes grown in soil treated with 2:3:2. The second radish harvest gives similar results with yields increased by 60%, where algal biomass has been added to the soil, an increase equal to that seen where 2:3:2 had been added. The increase in yield for the first Swiss chard harvest from soil treated with algal biomass is also comparable with the increase in yield from soil treated with 2:3:2 when compared with the untreated soil. Interestingly, the second harvest shows yields from algal-biomass treated soil are higher than that of the 2:3:2 treatment. In the final harvest, Swiss chard yield from soil treated with algal biomass is on average, 45g.plant^{-1} compared to <20g.plant^{-1} for 2:3:2.
3. The use of IHRAP algal biomass applied directly to soil as an amendment significantly increases crop yields of radishes and Swiss chard, compared with untreated soil ($p>0.05$).
4. These increases in crop yield for radish were comparable to increases seen with the use of 2:3:2.

5. ALGAL BIOMASS RECOVERY AND ITS USE IN FOLIAR FEEDS: A REVIEW

5.1 INTRODUCTION

Foliar feeding or foliar fertilising is becoming increasingly popular, although a still somewhat controversial practice of applying liquid fertilisers to plant leaves. The underlying principle is that stems, buds, twigs and most especially leaves will readily absorb nutrients that are applied as a solution. Foliar fertilisation is used in both conventional and alternative production systems to enhance crop nutrition (Kuepper, 2003). It is seen as especially useful as a means of supplying supplemental doses of micronutrients and trace elements such as Mg, S, Fe, Mn, Zn, B, Cl, and Na but can also used for macronutrients such as N, P and K (Davis, 2004; Kuepper, 2003; Tejada and Gonzalez, 2003). The technique is used in many applications such as spraying nutrients on fruit-setting crops like tomatoes and cucumbers to increase yields and on such leafy greens as lettuce and spinach to speed maturity and increase storage life (Donelan, 1988). European grape growers use foliar feeds in their vineyards, and Chinese farmers similarly treat heading grain crops to increase yields (Donelan, 1988). Turf managers spray golf courses (as well as cricket, rugby and soccer fields) to help grass green rapidly, and some large commercial farmers use foliar feeds to prevent frost and drought damage (Donelan, 1988). Other farmers spray regularly with liquid kelp to reduce aphid and red spider mite attacks or to control botrytis on strawberries and powdery mildew on rutabagas (turnips) (Donelan, 1988).

5.2 COMPOSITION

In their most basic form, foliar feeds can be made from weeds, animal manures or seaweed, either wet-harvested from pontoons, or collected from the beach and suspended in water. This is time-consuming and small amounts of nutrients are recovered. Commercially available foliar fertilisers, however, are often complex concentrations of organic or inorganic fertilisers plus trace elements etc. Foliar fertilisers can also be derived from natural products such as seaweeds (e.g. Kelpak) and fish emulsions (e.g. Seagro) that not only contain most macro- and micronutrients but may also contain amino acids, vitamins B1, B2, C, E, plant hormones (auxins, cytokinins), growth stimulants, amino acids and other beneficial substances (Kelpak, 2005; Davis, 2004; SeaGro Superkel pamphlet, 2004; Arthur *et al*, 2003; Zhang and Schmit, 2000; Zhang, 1997; Crouch and Van Staden, 1993a; Borowitska, 1988; Donelan, 1988; Senn, 1987). Foliar feeds can also be made from a variety of other ingredients including kitchen wastes, fish meal (Donelan, 1988) and micro-algae (Shabaan, 2001). The range of ingredients and manufacturing techniques will give an array of different nutrients and concentrations with the accompanying variation in performance.

This review will focus predominantly on foliar fertilisers derived from algae (including seaweed) extracts and similar organic-based ‘biofertilisers’.

5.3 PLANT GROWTH PROMOTERS

To gain an understanding of the effect of plant growth promoters, it is necessary to understand the basics of plant hormones, where these are produced and their role in plant growth and development. The following descriptions are from Raven *et al* (2004). Plant hormones are the main internal factors controlling growth and development. Auxins are important plant hormones produced by growing stem tips, young leaves and in developing seeds and are transported to other parts of the plant where they may either promote or inhibit growth. Auxins cause differentiation of vascular tissue and apical dominance in stems, whereas in roots it induces adventitious roots on cuttings while inhibiting growth in the main system. It inhibits leaf and fruit abscission while stimulating ethylene synthesis and fruit development. Ethylene is produced in most tissue in response to stress especially in tissues undergoing senescence (maturation) or ripening and causes fruit ripening, leaf and flower senescence, and leaf and fruit abscission. Cytokinins are produce mainly in the root tips and promote cell division, shoot formation and growth of lateral buds. Gibberellins are produced in the young tissues of the shoot and developing seeds, possibly also in roots and are responsible for hyperelongation of shoots via cell division and cell elongation, induction of seed germination, stimulation of flowering in long-day plants and biennials and regulation of production of seed enzymes in cereals. While there is ample scientific literature on chelating agents, the simplest and most fitting information came from the JH Biotech, Inc. website (2005). Chelating agents are important as they determine the bioavailability of essential trace metals and nutrients. Organic acids such as citric acids, malonic acid and some amino acids act as chelating agents. In order to prevent precipitation of absorbed nutrients, resulting from the interaction of nutrients upon entering plant cells, cationic nutrients will immediately form chelates with organic acids thus enabling the nutrients to move freely inside the plants. Natural chelating agents do not share the problems of the synthetic forms and are state-of-the-art technology for delivering selected mineral and trace elements with maximum bioavailability, tolerability and safety (JH Biotech, Inc, 2005).

5.4 ALGAE AS A SOURCE OF GROWTH PROMOTERS

The beneficial effects of algae on plant growth have been recognised by plant growers for centuries (Crouch and Van Staden, 1993a; Senn, 1987). Zhang (1997) gives a brief history of the scientific thinking with regards to the benefits of algal (and particularly seaweed) application: Initially, enhanced plant growth with seaweed application was attributed to its soil conditioning properties but later, it was shown that increased trace element supply could explain only some of the beneficial effects of seaweed. Low rates of seaweed extract were shown to promote plant growth significantly and it was subsequently suggested that organic compounds, rather than mineral elements, have been responsible for improved growth. It was not until recently that the researchers began to discover the possible reasons for these dramatic effects and some researchers consider the exact mechanisms behind the beneficial growth responses as still not fully understood (Crouch and Van Staden, 1993a). The mineral content alone cannot account for the extent of the favourable results observed and authors have attributed this to naturally-occurring plant growth regulators or plant hormones in algae (Zhang and Schmit, 2000; Crouch and Van Staden, 1993a; Zhang, 1997; Borowitska, 1988;

Senn, 1987). Young (in Senn, 1987) studied the effect of seaweed extract on the roots of plants and found that seaweed extracts used as regular foliar sprays and soil feeds promoted root development in a range of crops including wheat, sunflowers, beans, corn, peas and grasses and reports that other plant studies have produced similar results. Senn (1987) attributes these results to the presence of cytokinins as these can affect nutrient uptake into the roots of plants. Accelerated uptake of nitrates, phosphorus, potassium and calcium into the plant roots have been attributed to the presence of cytokinins (citation needed).

5.5 BROWN SEAWEEDS

Senn (1987) established that brown seaweeds (Phaeophyta) contain cytokinins, gibberellins, and indoles which are natural plant growth regulators. Over 70 microelements and essential micronutrients are found in brown seaweeds e.g. Fe, Cu, Zn, Mo, B, Mn and Co, all of which are necessary for healthy plant growth and development (Senn, 1987). It has also been reported that seaweed releases unavailable minerals from the soil and that these micronutrients can serve as co-factors that activate enzymes (Senn, 1987). According to Senn (1987) many seaweed products also contain a chelating carbohydrate known as mannitol, which chelates micronutrients into forms that are readily available for plant use. Other studies to date have concentrated on specific chemical extracts produced by seaweeds, nutrient and organic value (Nardi *et al*, 2004; Zhang and Ervin, 2004; Zhang and Schmit, 2000). A study by Zhang and Schmit (2000) describes seaweed extract as an exogenous hormone-containing product that was tested on tall fescue (Festuca arundinacea Schreb.) and creeping bentgrass (Agrostis palustris Huds. A.) resulting in improved growth and attributed to increased antioxidant concentrations.

5.6 MICROALGAE

Borowitska (1988) examined micro-algal extracts, also known to stimulate the growth of plants and attributes this, at least in part, to the presence of auxins, gibberellins, cytokinins and other hormones as does Shaaban (2001) in a study on the freshwater green alga Chlorella vulgaris. El-Fouly *et al* (1997) also make mention of the existence of chelating agents in C. vulgaris which when extracted and applied as a foliar feed facilitates penetration of elements through leaves. Micro-algae are also able to produce most vitamins, depending on species, stage of growth, nutritional status and photosynthetic rate, as well as the natural ethylene-releasing chemical 1-aminocyclopropane-1-carboxylic acid, which may be responsible for some of the growth stimulating effect of algal extracts (Borowitska, 1988). At that time (1988), the possible application of micro-algal extracts in horticulture and agriculture had not been explored although the use of the algal biomass for ‘green manuring’ or as biofertiliser had been considered (Borowitska, 1988). It appears that most research in the field of growth promoters has remained focused on macroalgae or seaweed, on the promotion of blue-green algae in the rice paddies of India and China or in situ soil algae (Metting, 1988). Algal biomass harvested from an algal turf scrubber (ATSTM) treating dairy wastewater was shown to have a balanced N:P ratio (Mulbry *et al*, 2005) which made it ideal as an organic fertiliser.

5.7 COMMERCIAL FOLIAR FEEDS

Commercially available products utilising algal foliar feeds generally appear to be using seaweed which is marketed as an "organic" alternative to conventional inorganic fertilisers. A well-known brand in South Africa utilises kelp (Ecklonia maxima) in the manufacture of foliar feeds and other products (Kelpak, 2005). The products were developed on the basis of research by B.C Featonby-Smith and I.J. Crouch, as well as a number of studies done by these authors, as well as J. van Staden and others (Kelpak, 2005). Manufacturers' claims match those of the scientific research outlined above. Products are "....packed with minerals, vitamins, amino acids and natural growth hormones. Seaweed is exceptionally beneficial to plant life. It provides essential nutrients while simultaneously improving the soil structure and increasing its water-holding capacity. It aids in frost protection and helps plants ward off fungal, insect and worm infestations. Its organic composition enables [the seaweed fertiliser] to act as both a year round slow release fertiliser and soil conditioner, ensuring that plants receive even quantities of nutrients over a period of time. As the decomposition of seaweed is much simpler than land plants, [the seaweed fertiliser] aids in the formation of humus, stimulating earthworm and microbial activity and improving the structure of the soil." (SeaGro Superkel pamphlet, 2004). Another manufacturer emphasises the role of the "growth bio-stimulants" and added value of soil conditioners. Yet another claims that the presence of algal polyose and polyphenols can promote the growth of plants and roots development, enhance photosynthesis, strengthen stalks, and increase plants ability to resist disease, pests, coldness and draught, improve quality, stimulate the maturity of fruitage, ameliorate the soil texture and increase soil water retention capacity.

5.8 LITERATURE RESEARCH RESULTS

The benefits of seaweed-based foliar feed (SBFF) given by both manufacturers and researchers are: enhanced photosynthetic activity and chlorophyll content (Zhang, 1997), increased drought resistance (Zhang and Ervin, 2004), disease resistance (Crouch and Van Staden, 1993b; Senn, 1987; Featonby-Smith and Van Staden, 1983) enhanced growth and development and therefore increased marketable yields (Shaaban, 2001; Zhang, 1997; Atzmon and Van Staden, 1994; Crouch and Van Staden, 1993a&b; Senn, 1987; Featonby-Smith and Van Staden, 1983) and enhanced shelf life. Impressive increases in yield through the use of foliar feeds are well documented in both scientific and popular literature(Citation).

5.8.1 Yield

Some of the earliest scientific non-root plant-feeding studies were done in the 1950's with plant uptake from 100 to 900% more effective when nutrients were applied as a foliar feed instead of into the soil (Donelan, 1988). Since then many studies have been conducted into the yield and quality of crops treated with SBFF as a foliar spray (Atzmon and Van Staden, 1994; Crouch and Van Staden, 1993a&b; Senn, 1987; Featonby-Smith and Van Staden, 1983). Positive results were obtained for yields of potatoes, lettuce, cauliflower, tomatoes, citrus, sweet potatoes, apples, strawberries, cucumbers and clover. Apricots, cherries, peaches, and plums showed increase in both quality and quantities of fruit (Senn, 1987). Experiments by Senn (1987) into cut flower production (long stem roses) achieved a 32% increase and cotton yielded up to

29% due to increase boll number per unit area. Foliar applications of SBFF on Swiss chard improved the growth significantly, irrespective of whether it was applied as a foliar spray alone, or in conjunction with soil applications of an inorganic fertiliser (Senn, 1987). Shaaban (2001) records a 140% yield weight increase and a 40% increase in grain weight using a green alga-based foliar feed. FoliarFert (2005) state that it is 12 and 100 times more effective to foliar-feed a plant in terms of nutrient quantities required and the speed with which those nutrients were utilised, compared to soil applications). Arthur *et al* (2003), Shaaban (2001), Zhang (1997), Atzmon and Van Staden (1994), Crouch and Van Staden (1993a&b), Senn (1987) and Featonby-Smith and Van Staden (1983) all report improvement in the marketable yield from the application of SBFF during plant growth. Arthur *et al* (2003) reports that the auxins and gibberellins found in one SBFF "effectively increase the fruit set and size" in tomatoes, cucumbers, aubergines and peppers, but admits to no effects on some stone fruits. Davis (2004) reports other researchers achieving results of a 24% increase in bean yields, a 17% and a 99% increase in tomato yields and early yields in cucumber.

5.8.2 Stress Tolerance

Senn (1987) reports on the effects of growth regulators on stress resistance and particularly the plant's ability to withstand changes in temperature and drought conditions by aiding changes in the metabolic pathways thereby permitting the roots access of extremely low moisture levels not normally available to plants. This has been substantiated by preliminary field trials on dry land cereal crops in Canada (Senn, 1987). Meek and Oosterhuis (1993) explain increased drought tolerance when using foliar feed, as plants make osmotic adjustments to cells by increasing organic ions or solutes. These inorganic ions and solutes can be supplied via foliar feed to increase drought resistance. Senn (1987) and later Featonby-Smith and Van Staden (1983) attribute increased drought resistance to increased speed of the healing of cut surfaces and an induced development of a large number of roots. Kuepper (2003) explains increased pest and disease resistance in foliar fed plants due to the natural resistance exhibited by properly-nourished plants. Increased insect and disease resistance, particularly to nematodes, are other properties observed in plants sprayed with SBFF (Crouch and Van Staden, 1993b; Senn, 1987; Featonby-Smith and Van Staden, 1983). Senn (1987) showed 98% reduction in the population of *Paratylenchus spp*. pin nematodes; 48% reduction in *Fusarium roseum* on Kentucky Bluegrass turf. In addition, seaweed extract applied as a foliar spray on apples appeared to suppress the reproduction rates of mites (Senn, 1987). Both popular and scientific literature report resistance to fungal diseases by plants treated with seaweed extracts. Senn (1987) that powdery mildew on leaves on cantaloupe (spanspek) plants could be reduced by application of SBFF. Zhang (1997) maintains that cytokinin-containing foliar feeds assist in stress tolerance by replacing the endogenous cytokinin, the production of which is reduced under stress conditions.

The literature, however, is filled with mixed and contradictory results on the effectiveness of SBFF products. In the same review, Davis (2004) cites three examples of researchers finding SBFF had no affect at all on crop yields. McConnel *et al* (1998) reported that foliar fertilisation with urea only increased cotton lint yield significantly when soil-applied N was low. It appears that there are numerous factors which affect the efficacy of foliar feeds including crop type, weather patterns and stress, soil conditions and fertility, rate of application and composition of the extract used (Davis, 2004; Kuepper, 2003; Tejada and Gonzalez, 2003; McConnell *et al*, 1998). This is due to the complex dynamics of plant nutrient uptake which are dependent on crop growth stages (Tejada and Gonzalez, 2003).

5.9 ADVANTAGES OF FOLIAR FEEDS

Apart from the obvious advantages of increased crop yields and quality, drought and disease resistance etc, foliar fertilisation has other advantages over fertilisers applied directly to the soil. A major advantage of using foliar feeds is that they are fast-acting, and able to cover the time lag between fertiliser application and uptake of the applied nutrient by plant roots (Tejada and Gonzalez, 2003). Foliar fertilisation is therefore particularly useful for supplying nutrients required in the early stages of development (Tejada and Gonzalez, 2003) or following stresses such as water stress, transplant shock, hail damage or other weather extremes (Kuepper, 2003; Donelan, 1988). Nutrients can be supplied in the correct form and absorbed right at the site where they will be used for the production of the complex chemical compounds needed for growth produced in the leaves via photosynthesis. In addition, foliar fertilising does not rely on the presence of soil moisture for the absorption of the nutrients. They are therefore fast-acting (Donelan, 1988) and can bring about immediate improvement in plant health and growth (FoliarFert.com, 2005). Foliar fertilisation has been claimed as being from 8 to 20 times as efficient as ground application, in terms of nutrient absorption (Kuepper, 2003). Foliar feeds are therefore used in more dilute amounts than liquid soil fertilisers and commercial foliar fertilisers are generally lower in concentration of N, P and K than conventional inorganic fertilisers, based on the argument that it is the variety of micronutrients that make them so effective rather than concentrations (Donelan, 1988). As Liebig's Law of the Minimum – a basic principle of plant science – points out, “the nutrient in least supply is the one that limits plant growth,” (Donelan, 1988). The mere presence of a particular chemical species in the soil does not guarantee the effective assimilation by plants, as nutrients are not always available in the forms that plants can use, or in the quantities needed. Soil conditions, such as pH, moisture content, or temperatures affect availability of some nutrients to the plant root (FoliarFert.com, 2005). As foliar feeds use lower concentrations of NPK, environmental problems such as eutrophication of nearby water bodies, associated with leaching of soils and runoff of fertiliser nutrients, can be mitigated to large extent (Tejada and Gonzalez, 2003). In addition, when micronutrients become a limiting factor, water, fertiliser and other high-energy production inputs are wasted (FoliarFert.com, 2005). Timeous applications of micronutrient foliar feed would therefore also maximise utilisation of these inputs. Although foliar fertilisation does not totally replace soil-applied fertiliser, it does increase the uptake and hence the efficiency of the soil-applied material (Tejada and Gonzalez, 2003; Kuepper, 2003).

5.10 DISADVANTAGES OF FOLIAR FEEDS

Foliar feeds do, however, have some disadvantages as they can be costly to procure and apply, especially on a large scale. They also do not build up degraded soils or supply organic matter for prolonged fertility (Donelan, 1988) and cannot replace a sound soil-fertility program (Kuepper, 2003; Tejada and Gonzalez, 2003; Davis, 2004). Despite efficient nutrient absorption being possible, efficiency is not always achieved in actual practice, often due to inattention to the principles of foliar feeding. The amount of foliar feed that can be applied at any one time is limited by the leaf surface area and therefore several applications are necessary to meet the required quantities (Tejada and Gonzalez, 2003). It would therefore be difficult to meet the macronutrient needs by foliar fertilisation alone (Davis, 2004). The economics of foliar feed is difficult to predict as it is dependent on how successful applications are and on whether it is the most economical way of supplying this nutrition (Kuepper, 2003). The economics of foliar feed application therefore depend on the same factors that determine the effectiveness of the foliar feed itself, crop type, weather patterns and stress, soil conditions and fertility, rate of application and composition of the extract used (Davis, 2004; Kuepper, 2003; Tejada and Gonzalez, 2003; McConnell *et al*, 1998). Kuepper (2003) states that the economic value of foliar fertilisers' is generally considered greater for horticultural uses rather than for use on agricultural crops. It is therefore frequently used to supplement a constituent that is lacking, or used as a booster during stress periods such as cold, drought, transplanting and reproductive growth phases than as a basic fertilisation regime (Davis, 2004; Zhang and Ervin, 2004; Donelan, 1988; Senn, 1987).

5.11 PRACTICALITIES OF FOLIAR FEED APPLICATION

There are a number of basic principles for use of foliar feeding which must be applied to achieve optimum results. Firstly, it is important to apply the foliar feed at the correct time. Plants need to have developed enough leaf surface area to absorb a feed before applications can be used effectively (Donelan, 1988). During periods of greatest growth activity plants often experience stress and additional nutrients and hormones (cytokinins, auxins, gibberellins) supplied in the form of foliar feeds can enable efficient plant up-take of the required substances to enhance photosynthesis and allow healthy growth (Davis, 2004; Zhang and Ervin, 2004; Kuepper, 2003; Tejada and Gonzalez, 2003; McConnell *et al*, 1998; Zhang, 1997; Donelan, 1988; Senn, 1987). To facilitate efficient use of foliar feed, it should be applied when the plant is not too wet or too dry, when the plant is cool and filled with water (turgid). The optimum temperature for application is about 22°C with decreased efficiency at 26°C or above; the spray will be less effective as stomata close at high temperatures to limit evapo-transpiration (Kuepper, 2003; Donelan, 1988). Wind is also an important consideration as it increases evaporation rates decreasing the mobility of solutes and time for plant uptake (Kuepper, 2003; Donelan, 1988). Foliar feed applied in the early morning, late afternoons or on overcast days, when wind is minimal, plants are cool, evapo-transpiration is low and stomata are open, are most effective. Absorption is further enhanced when weather conditions are humid and moist, and the presence of heavy dew on the leaves facilitates foliar feeding (Kuepper, 2003). Both the upper and lower leaf surfaces should be coated where practical, as most stomata are located on the underside of leaves and the lower leaf surface often stays wet longer to facilitate absorption (Kuepper, 2003; Donelan, 1988).

Finely atomised (as fine a mist as possible) foliar feeds achieve the best results and the addition of a surfactant to the solution decreases surface tension on the leaf and may increase absorption (Kuepper, 2003; Donelan, 1988). It is also best to avoid spraying in direct sunlight as the formation of droplets on the leaves that act as lenses for the sunlight to focus burns on the leaves (FoliarFert.com, 2005).

Application rates given in the literature vary between products and crops, from once to four times a week, from planting to harvesting and through specific growth stages.

As outlined in the previous sections, application during times of stress appears to be most effective e.g. at transplanting, in the crop's final week of growth, when the vines start to run (melons), when the fruits are reaching full size, at the first blossom set, every 10 days or so during harvest (tomatoes), when heads or ears start to form (grains) or after extreme weather (Donelan, 1988)

5.12 MANUFACTURE OF FOLIAR FEED

Most of the scientific and manufacturer's literature does not describe the detailed process of manufacturing foliar feeds as this is proprietary information. Most studies on foliar feeds are centred on the testing of already available commercial products (Davis, 2004; Arthur *et al*, 2003; Atzmon and Van Staden, 1994; Zhang, 1997; Crouch and Van Staden, 1993a&b; Featonby-Smith and Van Staden, 1983), the by-products of other processes (Tejada and Gonzalez, 2003) or one or more elements, Zn, Bo etc (Williams *et al*, 2004; Ling and Silberbush, 2002; Oosterhuis and Steger, 1999; McConnell *et al*, 1998). The one known exception to this is a study done by Shaaban (2001) which will be dealt with separately. While the focus of this review centres on seaweed-based foliar feeds, other naturally-derived foliar feeds can be made from fish emulsions, dried blood, bat guano, worm castings, compost teas, manure teas, humates, molasses, milk, B vitamins, and herbal extracts of weeds and plants like stinging nettle and horsetail (Kuepper, 2003; Donelan, 1988). Popular articles are available describing basic methods of making foliar feeds based on some of the aforementioned ingredients and aimed at the organic gardener. Donelan (1988) describes a number of ways to make foliar sprays. Outlined below is a basic recipe for a gardener for making weed-based foliar feed:
Fill a 100 to 200 ℓ barrel with weeds and water, in a ratio of *ca*1 kg of weeds: 5 to 7 ℓ water). After two or three weeks, the solution will be ready to use. Filter the liquid before use to avoid clogging the sprayer. Wet crop leaves thoroughly. Four litres should treat approximately 9.3m^2. Keep filling the barrel with water and weeds.

5.13 SHAABAN'S STUDY (2001)

Studies done by Shaaban (2001) at the National Research Centre in Cairo, using freshwater green algae in a foliar feed showed markedly better yields than micronutrient foliar fertiliser. As this paper describes in detail methodology of producing foliar feed from micro-algae, it has been summarised separately below. In Shaaban's (2001) study, foliar feed was made from micro-algae *Chlorella vulgaris* and tested on wheat (*Triticum aetivum* L. Var). The micronutrient against which the algal foliar feed was tested contained the following nutrients: 5.2% Mn, 0.65% Zn, 0.65% Cu, 0.02% Mo (m/v) in a spray solution of 2ml of the concentrate per litre. The algae cell extract was applied in four different treatments namely: T1 at 25%, T2 at 50%, T3 at 75%, T4 at 100% algal cell extract.

5.13.1 Method

Shaaban's (2001) method of making foliar feed from C. vulgaris was conducted on a smaller scale using a more scientific methodology than described by Donelan (1988). Algae were firstly washed with distilled water, then centrifuged, frozen and subsequently centrifuged to obtain a clear sap. This sap was then made up at three different dilutions namely, 25%, 50% and 75% with distilled water and a fourth treatment was the 100% cell extract (Shaaban, 2001).

5.13.2 Nutrient Uptake

The algal extract was then tested by application onto wheat seedlings as foliar feed in the same quantities as the micronutrient foliar feed. The wheat shoots were then assayed for N, P, K, Mg, Ca, Fe, Mg, Zn, Cu. Nutrient uptake was calculated and the T2 (50% conc.) treatment seemed an adequate concentration for desired nutrient uptake. The results of this experiment showed firstly that as concentrations of algae increased the uptake of P, Fe, Mn, Cu in the shoots increased which Shaaban (2001) attributed to the "reasonable presence" of these elements in the algae, and stated that this was particularly noticeable with phosphorous, an element which is not present in many of the known foliar fertilisers. The increased level of nutrient uptake was also ascribed to the presence of nutrients in the cell sap in organic form and thus reportedly able to be directly involved in metabolism. Shaaban (2001) also refers to previous studies done with El-Fouly *et al* (1997), stating that amino acids derived from proteolysis, can also act as chelating agents, facilitating penetration of elements through leaves. In agreement with studies into the agricultural use of seaweeds by Aztmon and Van Staden (1994), Senn (1987) and Featonby-Smith and Van Staden (1983), Shaaban also mentions the role of amino acids from C. vulgaris in facilitating micronutrient uptake through the plant roots. Shabaan (2001) showed that the algal treatments had nutrient balances (N:P and N:Fe) closer to the desired levels in comparison to the micronutrient treatments, and the control in which the nutrient balance exceeded the desired level. For the nutrient ratios for P:Mn, P:Zn and Fe:Zn, the control experiments had much lower values than the algal treatments. From the conclusions of Shaaban (2001), it can be deduced that the foliar feeds produced from algae enhanced P and Fe uptake in the wheat shoots.

5.13.3 Yield

The most remarkable results produced by Shaaban (2001) were that the fresh and dry weight yield results for the different treatments showed markedly different trends. With fresh weight, the treatments showed little difference between micronutrient foliar feed treatments and algal foliar feed treatments. However, when dry weight was measured, the algal treatments showed much heavier dry weights in comparison to micronutrient treatments. Shabaan (2001) attributes this to a higher nutrient uptake from the wheat shoots in the algal treatments. The fact that fresh weight yields are similar must indicate that plants in micronutrient treatments as well as the control had higher levels of water uptake as opposed to the algal treatments.

Shaaban (2001) also measured yield as dry spike weights per pot and 100 grain weight. The results showed that algal treatments of 50% concentration and above produced substantially higher dry weight yields than micronutrients. Shaaban (2001) attributes these findings to the possible presence of "hormones, enzymes and vitamins which may improve nutrient assimilation and solute translocation from leaves to grains" in the algal foliar feed which led to higher yields in the wheat grains. Figure 5.1, taken from Shaaban (2001), illustrates these results as percentage increases in grain weight for the different treatments used in the study.

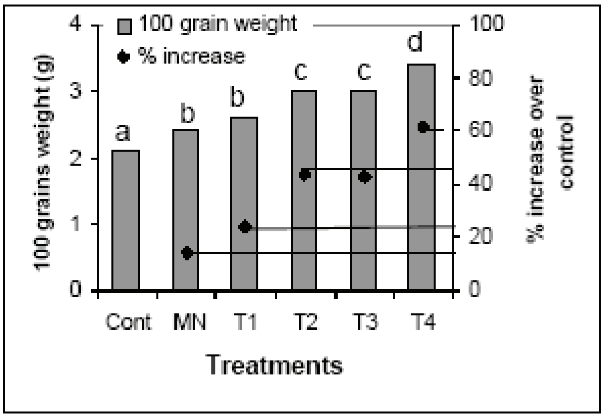


Figure 5.1. 100 grains weight (g) as affected by micronutrients (MN) and different concentrations of the algae extract (bars with same letters are not significantly different, P = 0.05). T1=25% algal conc., T2=50%, T3=75% and T4=100%. (Shaaban, 2001)

Shaaban (2001) concludes that green algae extract is a superior foliar feed than micronutrients. A 50% concentration of algae extract can lead to a 140% yield weight increase and a 40% increase in grain weight, and proposes that more studies be done on larger scale production of algae as a foliar feed.

5.14 CONCLUSIONS

From the literature on foliar feed use, contents and manufacture, the following conclusions were drawn:

1. Macroalgae (seaweeds) contain growth hormones such as cytokinins, auxins, indoles and gibberellins as well as chelating agents and micronutrients and is used in the manufacture of foliar feeds. Although microalgae also contain these, they are not widely used in the foliar feed production.
2. Benefits of seaweed based foliar feeds are: enhanced photosynthetic activity and chlorophyll content, increased drought and disease resistance, increased marketable yields and enhanced shelf life.
3. Crop type, weather patterns, stress conditions soil conditions and fertility and composition and concentration of the extract affect the efficacy of algal-based foliar feeds. Timing and method of application also affect efficacy.
4. Foliar feeds are fast-acting and can therefore be used to help plants recover quickly following high stress events such as hail damage, transplantation etc.
5. Foliar feeding is costly and therefore best used on high value horticultural crops.
6. The development of a practical method of producing foliar feed from microalgae on a large scale is needed.

   Microalgae harvested from the IAPS should contain most of the necessary components to produce an excellent foliar feed.

6 UNICELLULAR ALGAL BIOMASS APPLIED AS A FOLIAR FEED: LABORATORY STUDIES

6.1 INTRODUCTION

Algal biomass from the IAPS consists of a consortium of microalgal species. In order to manufacture a foliar feed from the microalgae, it was necessary to develop a methodology of cell sap extraction.

6.2 MANUFACTURING METHODOLOGY

Algal biomass was harvested from the ASP and pumped into a settling cone after which it underwent secondary settling for two days (Figure 6.1). Thickened algal slurry was obtained and used for the manufacture of the algal foliar feed. Foliar feed was manufactured from algal biomass produced in the HRAP using a combination of methodologies, namely: the manual rupturing of cells by grinding biomass with quartz sand with a pestle and mortar, followed by freeze-thaw methodology using liquid nitrogen to crack cells and centrifugation to separate cell sap (Figure 6.2).

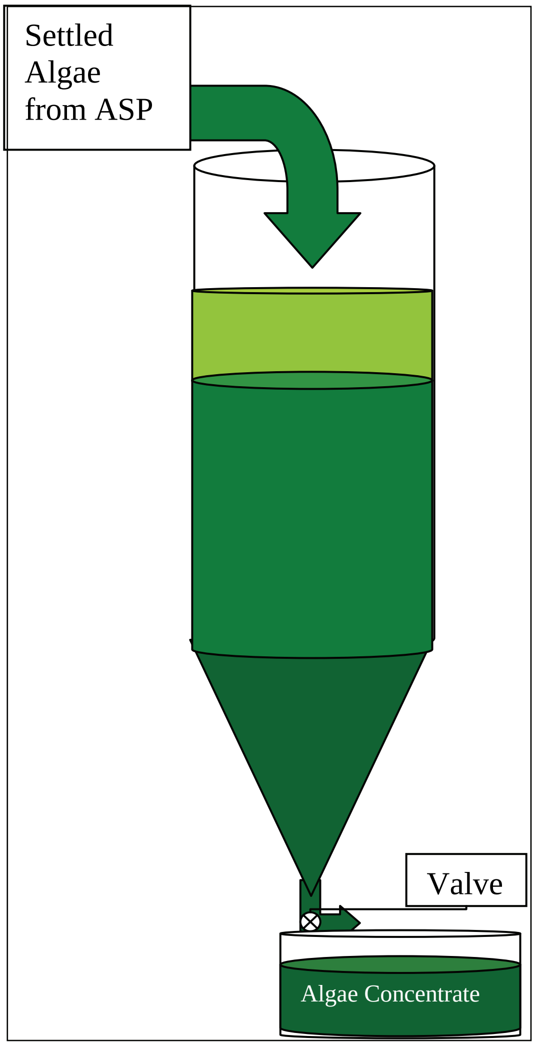


Figure 6.3: Secondary algal settling tank

Concentrated algal biomass from the settling cone was first centrifuged for 10 minutes at 2000 rpm (RCF = ?) and the supernatant decanted. Total nitrogen and phosphorous values were determined for concentrated algal biomass as well as supernatant. Algal pellets were weighed and transferred into a mortar. Quartz sand was added and biomass was crushed manually using a pestle (Figure 6.2a). Liquid nitrogen was then added until all biomass was frozen (Figure 6.2b). This was left to defrost overnight. Defrosted biomass was then diluted to approximately 1200 mℓ and centrifuged at 5000 rpm for 10 minutes to remove cell walls and quartz sand. 5 mℓ of dispersant was added per litre of supernatant and sprayed on to plants as per foliar feed. Foliar feed was applied to all plants on the same day as manufacturing was completed to ensure maximum benefit before any possible degradation of plant extracts such as plant hormones, natural chelating agents and nutrients. Blank foliar feed and commercial foliar feed was also applied to controls on the same day. Foliar feed was applied on the plants on a weekly basis up until one week before harvesting.

Figure 6.24: Algal biomass with quartz sand for rupturing cell walls (a); liquid nitrogen added to algal biomass (b).

6.3 FOLIAR FEED TRIALS

6.3.1 Experimental Methodology

Two crops were selected for use in the foliar feed trials (Figure 6.3) due to their ease of cultivation and resistance to disease, namely bush beans (Contendor cultivar) and tomatoes (Kaki cultivar). Fruiting crop such as beans (Beckett *et al*, 1994; Featonby-Smith and Van Staden, 1993) and tomatoes (Crouch and Van Staden, 1992&1993; Featonby-Smith and Van Staden, 1983) were used for foliar feed trails in the literature and are better suited to the warm tunnel conditions than Swiss chard.

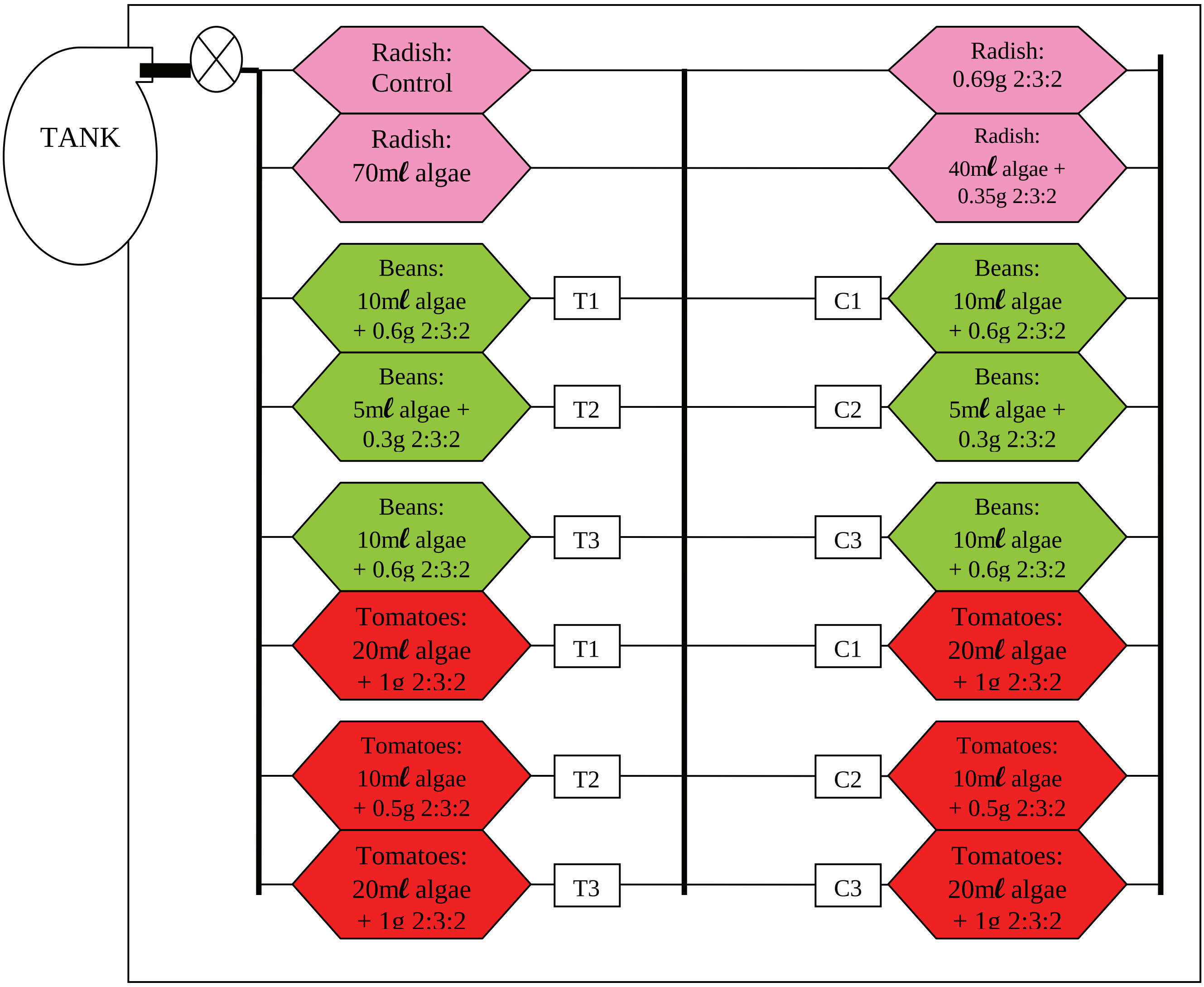


Figure 6.3: Tunnel layout and soil amendment rates for foliar feed and soil amendment trials**.**

Kaki cultivar tomatoes seeds (indeterminate growing cultivar) were propagated in seed trays and kept in a constant environment room with 8 hours of sunlight, a daytime temperature of 25°C and a night time temperature of 16°C. Tomato seedlings were planted out into plant bags once the soil amendments had been added (Figure 6.4). Tomatoes were trellised (Figure 6.5) and pruned to a single stem to avoid crowding and shading of plants. The three treatments for tomatoes were:

- T1: 20mℓ algae + 1g 2:3:2 soil amendment plus the algal foliar feed; with a control of 20mℓ algae + 1g 2:3:2 soil amendment rate and a blank foliar feed
- T2: 10mℓ algae + 0.5g 2:3:2 soil amendment rate plus the algal foliar feed; with a control of 10mℓ algae + 0.5g 2:3:2 soil amendment rate and a blank foliar feed
- T3: 20mℓ algae + 1g 2:3:2 soil amendment rate plus commercial foliar feed; with a control of 20ml algae + 1g 2:3:2 soil amendment only.

Kaki cultivar tomatoes take approximately 120 to150 days to reach harvest according to guidelines from the seed producer.

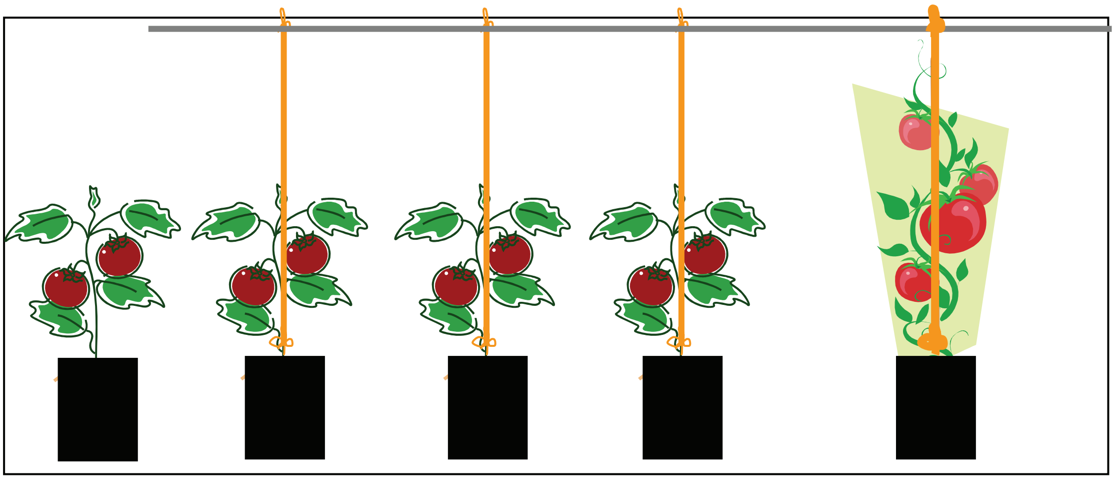


Figure 6.4: Tomatoes trellised using twine to support stems and the growing tip trained around the twine.

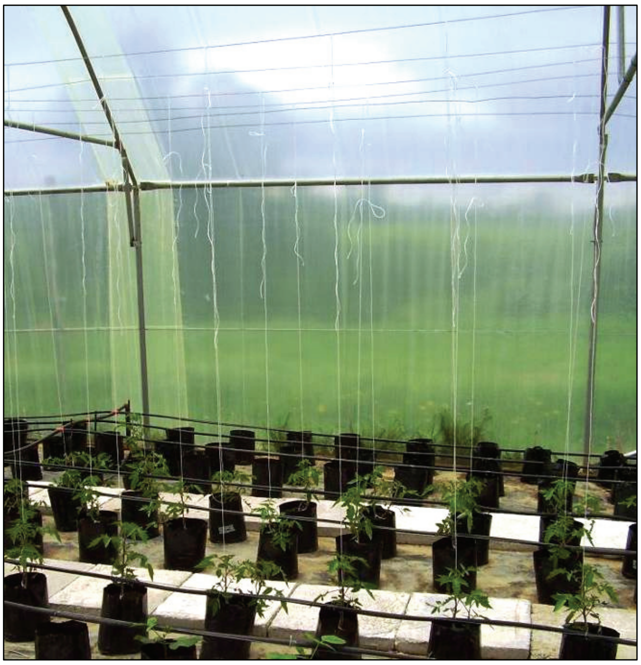


Figure 6.5: Kaki cultivar tomatoes trellised using twine

Bush beans (Contendor cultivar) were planted directly into the plant bags once the treatments had been added to the soil (Figure 6.6). The three treatments for beans were:

- T1: 10mℓ algae + 0.6g soil amendment rate plus the algal foliar feed; with a control of 10mℓ algae + 0.6g soil amendment rate and a blank foliar feed
- T2: 5mℓ algae + 0.3g soil amendment rate plus the algal foliar feed; with a control of 5mℓ algae + 0.3g soil amendment rate and a blank foliar feed
- T3: 10mℓ algae + 0.6g soil amendment rate plus commercial foliar feed; with a control of 10mℓ algae + 0.6g soil amendment only.

Contender beans take approximately 50-70 days to harvest (Gilbert and Hadfield, 1996).

Figure 6.6: Contender cultivar dwarf (bush) beans

2:3:2 quantities were based on recommended application rates for each particular crop (Gilbert and Hadfield, 1996). Algal quantities were based on the 2:3:2 equivalent of Kjeldahl nitrogen content. Foliar feed was manufactured according to methods described and sprayed on the relevant plants on a weekly basis up until harvesting.

6.3.1.1 Pest Control

Due to the warm, moist conditions in the tunnel in spring and summer it was necessary to spray preventatively against fungal infections. The broad spectrum fungicide Bravo 720 with chlorothalinol (720g/ℓ) will be sprayed every two weeks as a preventative treatment or at the first sign of infection. The pyrethroid (cypermethrin) insecticide (Garden Ripcord) was sprayed as a full cover spray every 2 weeks as a preventative treatment and at the first sign of infestation. The insecticide and the fungicide were applied on alternate weeks. A minimum of one week was allowed between the last pesticide applications and harvesting.

6.3.2 Harvesting Methodology

6.3.2.1 Tomatoes

All tomato fruit were harvested on the same day regardless of fruit colour, size or readiness (Figure 6.7). Fruit was counted, weighed and measured (height and diameter). A subsample of 5 fruit per treatment was dried at 100°C for 2 days to obtain dried weights. A subsample of 4 whole plants per treatment was also sampled. Soil was washed from the roots and air dried in order to obtain shoot and root weight.

Figure 6.7: Tomato fruit shortly before harvest. Note the single ripe fruit in the background**.**

6.3.2.2 Beans

All bean pods were harvested on the same day regardless of pod colour, size or readiness (Figure 6.8). All bean plants were removed from the soil and roots washed and air dried in order to obtain shoot and root weight.

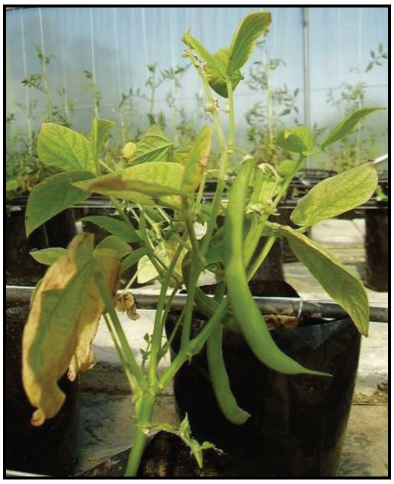


Figure 6.8: Bean with pods shortly before harvesting

6.3.3 Statistical Analysis

Statistical analysis was carried out using the Statistica 7™ package. Normality tests were performed to determine if a data set was normal. One way analyses of variance (ANOVA) was conducted on normal data sets to determine if there was a significant difference between treatments. Levene’s test was carried out to determine homogeneity of variance between treatments. These were followed by a post-hoc Sheffé test to show which treatment were significantly different from each other.

Kruskal-Wallis nonparametric ANOVA were conducted on non-normal data sets to determine whether differences between treatments were significant.

6.4 RESULTS AND DISCUSSION

6.4.1 Tomatoes

Results from the foliar feed trials on tomatoes were inconclusive. None of the treatments showed significantly higher growth rates or increased yield as a result of the application of foliar feed manufactured from the IAPS algal biomass. The application of commercial foliar feed increased average shoot weight and fruit weight marginally but differences were not significant (Figure 6.9).

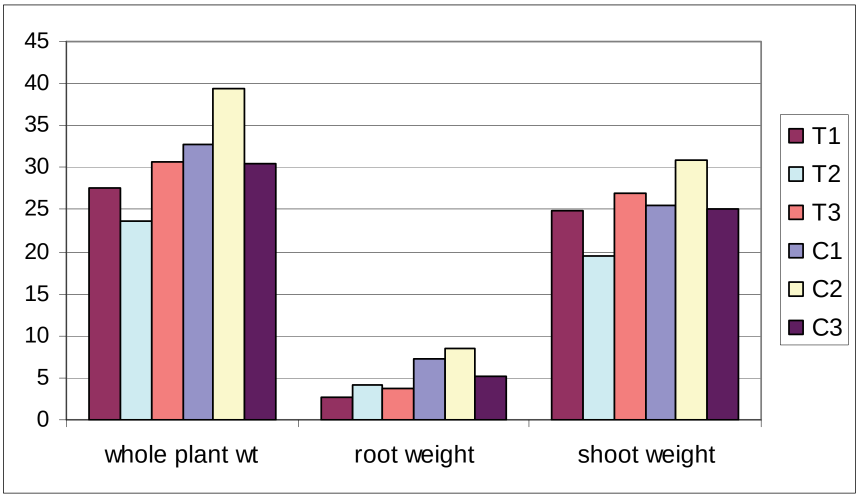


Figure 6.9: Average wet weights of tomato plants were not significantly different among treatments. (See Figure 6.3 for legend)

T2 had a marginally lower shoot weight but higher root weight than T1 or T3 and although this did not appear to affect the size and weight of the fruit (Figures 8.10 and 8.11), it corresponds to the number of tomatoes produced per plant. C2 had a similar inverse relationship between shoot weight and fruit size. Although C2 showed higher plant biomass, average weight and size of tomato fruits were smaller but number of fruit per plant was the second highest. (Figures 5.10 and 5.11).

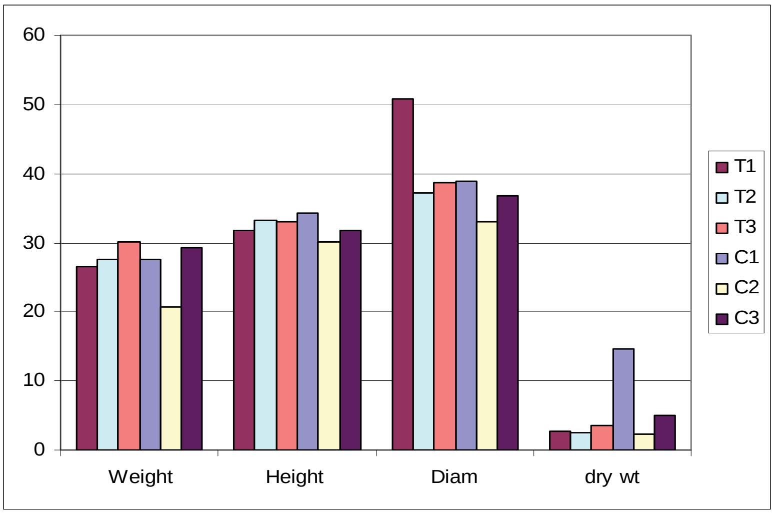


Figure 6.10: Average weights, diameters heights and dry weights of tomato fruit were not significantly different between treatments. (See Figure 6.3 for legend)

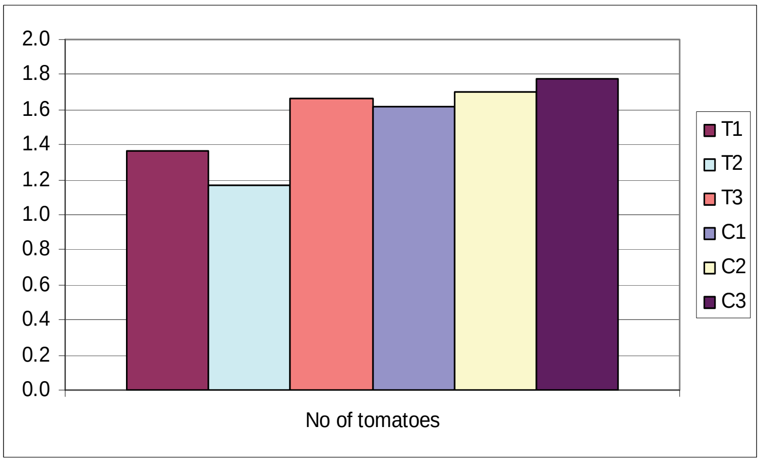


Figure 6.11: Average yield per plant was not significantly different between treatments. (See Figure 6.3 for legend)

Interestingly, T2 and its control C2 received half the quantities of soil amendment (algae and 2:3:2) that T1, T3 and their controls C1 and C3 received respectively. However, plant growth and yield in C2 were higher than T2 and T2 had the lowest yield of all treatments. Yet as there is no significant difference between T2 and C2, no definitive conclusions can be drawn from these observations and the result could be attributed to factors such as positioning, ventilation, natural variance in plant growth rates etc. Due to a large range in size of tomatoes on a single plant and therefore within treatments, data concerning tomato size and weight were not statistically normal which complicated statistical analysis and may have obscured trends (Figure 6.12).

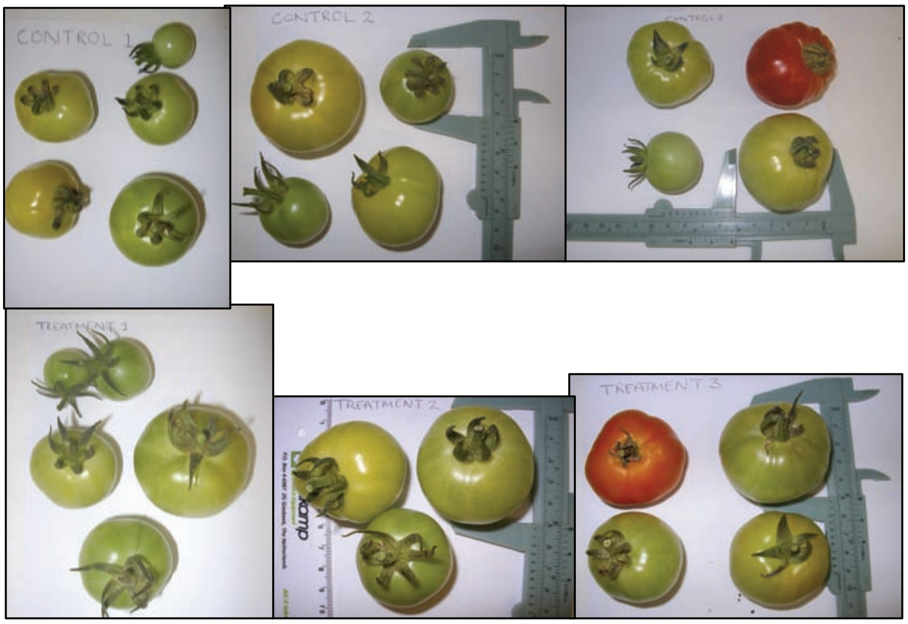


Figure 6.12: Tomatoes varied in size and colour within treatments as well as amongst treatments.

Although foliar feed manufactured from algal biomass did not increase yield or plant growth significantly, it should be noted that the commercial foliar feed also did not produce significantly higher yields in comparison to both controls and algal foliar feed treatments.

6.4.2 Beans

The results from the foliar feed trials on beans were similarly inconclusive. None of the treatments showed significantly higher growth rates or increased yield as a result of application of foliar feed manufactured from the IAPS algal biomass. The application of commercial foliar feed increased average root weight marginally but differences were not significant (Figure 6.13). Where plant shoot weight was on average higher (T1), root weight was lower suggesting shoot growth at the expense of root development. Again, these differences were not significant and definitive conclusions cannot be drawn from the data.

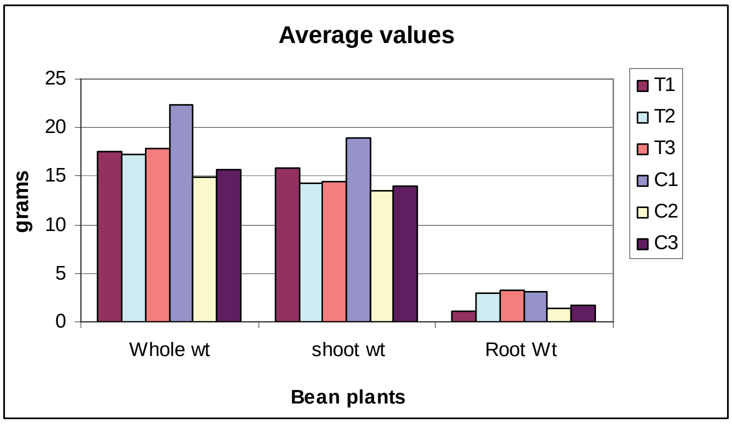


Figure 6.13: Average wet weights of bean plants were not significantly different between treatments. (See Figure 6.3 for legend)

Due to harvesting methodology of employing a single harvest, moisture content of bean pods at the time of harvesting varied which affected weight of the pods relative to size. The length of the pods, rather than weight therefore provided a better reflection of yield (Figure 6.14). T1 again showed marginally larger pod sizes overall followed by T2. T3, the commercial foliar feed, had slightly smaller pods. Again, no significant differences between treatments were established.

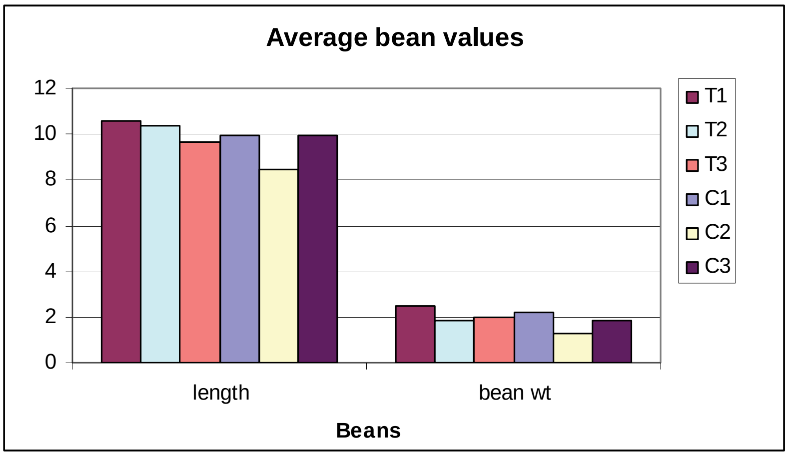


Figure 6.14: Average weights and lengths of bean pods were not significantly different between treatments. (See Figure 6.3 for legend)

The average number of pods per plant (Figure 6.15) gave another measure of plant yield. As with the pod length neither the algal nor the commercial foliar feed increased pod number or weight per plant significantly.

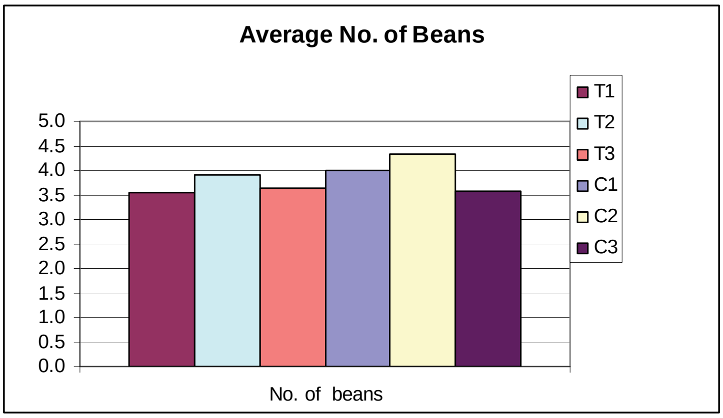


Figure 6.155: Average yield per plant was not significantly different between treatments**. (**See Figure 6.3 for legend)

As with the tomatoes, neither the foliar feed manufactured from algal biomass nor the commercial foliar feed produced significantly-increased yield or plant growth.

6.5 CONCLUSIONS

From the laboratory-scale experiments on foliar feed manufacture and trials, the following conclusions can be drawn:

1. Algal biomass produced from the IAPS can be harvested by secondary settling of algal slurry from the algal settling ponds of the IAPS.
2. Cracking of algal cells can be achieved through manual methods of grinding or thermal methods such as rapid freeze-thaw cycles. In commercial operations, this operation would be done using a variety of available industrial methods not listed here.
3. The production of a foliar feed from the algal biomass produced from the IAPS did not increase crop yield under the conditions tested. Notably, however, the commercial foliar feed did not significantly increase yield under the test conditions either.
4. A refinement in experimental design, longer term trials and detailed biochemical analysis of both the algal foliar feed and commercial foliar feeds should be undertaken to further examine this system.

7 UNICELLULAR ALGAL BIOMASS AS A FERTILISER: FIELD TRIALS

7.1 INTRODUCTION

Field trials were conducted in the scale-up of the laboratory studies on algal biomass soil amendment and to evaluate crop production under outdoor conditions. The field trials provided insight into the soil application of the HRAP algal biomass for the improvement of crop yields. Foliar feed application was not considered in this study.

7.2 EXPERIMENTAL METHODOLOGY

An experimental site was set up on Chamissonis Farm (Figure 7.1) (33°20’8”S 26°27’21”E), 8 km west of Grahamstown, Eastern Cape. The site was chosen for its relative flat topography, soil depth, sheltered location, northerly aspect and access to water.

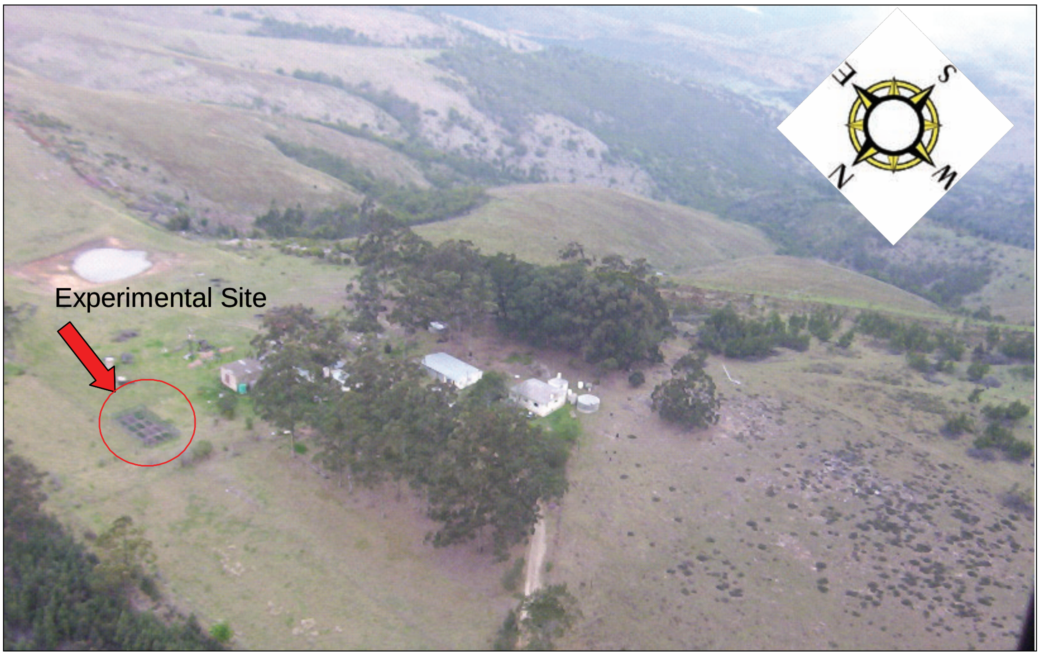


Figure 7.1: Aerial photograph of Chamissonis Farm showing the position of the experimental site.

The site had been under kikuyu grass for the preceding 10-15 years with no grazing or cultivation during that time. A visual assessment of the soil to a depth of 70cm revealed a relatively uniform structure. A random soil sample was analysed to determine soil type and chemistry and fertiliser application rates.

The site was prepared by removing grass using a tractor and ripper, followed by deep ploughing. The remaining grass was removed by hand. Fencing was erected around the site and the top covered with bird netting to secure it against crop damage by hail, birds and other animals. 12 plots of 1.5m x 3m were laid out and edged each with bricks (Figure 7.2).

Figure 7.6: Plots edged with bricks, fenced and ready for planting (1). Seedlings planted and irrigated (2). A dripper located at each seedling (3).

Drip irrigation was installed in all plots to allow irrigation of individual plants and minimise cross contamination of nutrients by flooding.

It was decided that two leaf crops and a root crop would be cultivated due to the differing nutrient requirements of each. Swiss chard, *Beta vulgaris* L.*cicla*; cabbage, *Brassica oleracea* L. var. *capitata*; and turnips, *Brassica rapa*, were selected for a number of reasons; namely, season, ease of cultivation and availability. Swiss chard can also be harvested numerous times allowing the experiment to run over two harvests (winter and spring). Turnips were chosen to test suitability of algae for root crops as these can be sensitive to nitrogen levels which can cause luxuriant growth of foliage at the expense of the root (Hartemink *et al*, 2000). The cultivars available at the time of planting were Starke Ayres' Early Purple Top Globe Turnip, Starke Ayres' Fordhook Giant Swiss Chard and Starke Ayres' Cape Spitz Sugarloaf Cabbage.

Four soil treatments were used for each crop including a control plot. The three experimental treatments were algae, fertiliser and a combination of algae and fertiliser. The crop and treatment were randomly assigned to the 12 plots which were numbered from East to West, and North to South as shown in Figure 1 below.

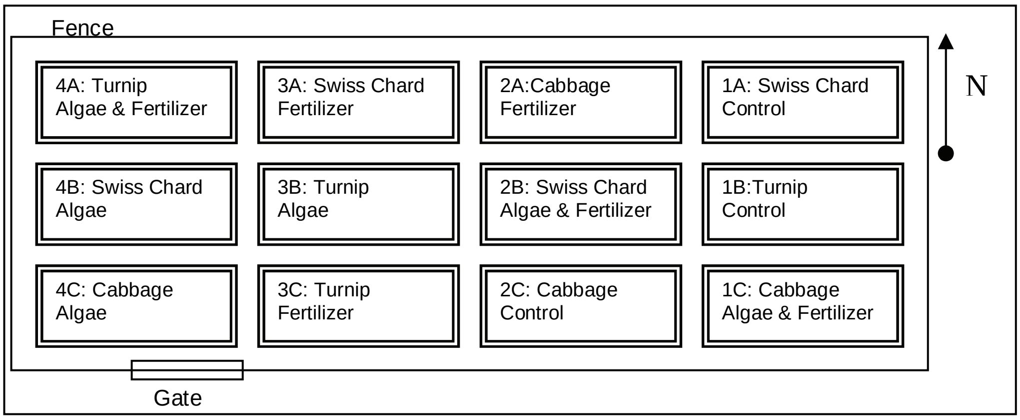


Figure 7.3: Randomised plots numbered from north to south, and east to west.

Commercial inorganic fertiliser 2:3:2 (N:P:K) was applied to designated 'Fertiliser' plots (2A, 3A and 3C), as well as 'Algae & Fertiliser' plots (1C, 2B and 4A) 20 days before planting according to Gilbert and Hadfield's (1996) recommended rates for each crop (Table 7.1).

Table 7.11. Recommended 2:3:2 fertiliser application rates (Gilbert and Hadfield, 1996).

Crop	**Recommended 2:3:2 application rates**
Turnip	45-60g/m^2
Swiss Chard	60-90 g/m^2
Cabbage	60-90 g/m^2

Algal biomass was applied to 'Algae' Plots 2B, 3B and 4C, and 'Algae & Fertiliser' to Plots 1C, 2B, and 4A, based roughly on recommended volumes for compost. An algal slurry was collected from the algal settling ponds of the EBRU IAPS pilot plant and 30 ℓ (15 ℓ for each row) applied to the relevant plots and dug into the soil calculated according to nitrogen application rate per hectare.

Cabbage and Swiss chard seeds were planted into inert sterile medium in seed trays at three times the number needed in order to ensure sufficient healthy seedlings of similar size for planting out. After 17 days, seedlings were thinned out and after a further 5 days were planted into the plots. Turnip seeds were sown directly into the appropriate plots. When planting, the healthiest seedlings of similar size were selected. Turnips were thinned out 58 days after planting.

The irrigation regime was based on the weather and the rainfall throughout the project period. Initially plants were irrigated regularly for short periods but as plants grew larger, irrigation was less regular but maintained for longer periods. Adequate irrigation was initially judged by filling the trough in which the spinach and cabbages were planted. Once growth was more established the irrigation was applied until soil was noticeably damp. Initially irrigation was as little as 10 minutes per day. Later on as much as 4 hours of irrigation was applied approximately once a week with occasional half-hour periods during noticeably drier spells.

The pesticide spraying regime was determined by constant examination of plants and sprayed as required. Garden Ripcord™ (active ingredient cypermethrin) was sprayed on after aphids were noticed on the cabbages in the control plot. Phostoxin was used to control moles when necessary.

In situ measuring and photography was used to document differences in growth rates after one month and again after the second month. Swiss chard was harvested 131 days after sowing and 79 days after seedlings were planted. According to Gilbert and Hadfield (1996), plants should be ready for harvest 55 days after planting. This estimate however, is given for ideal conditions. The second season's cabbage crop was harvested only 51 days after the first, as warmer weather and longer days increased growth rates. All the Swiss chard was harvested, weighed and measured on both occasions using the following method:
All leaves except the middle two were cut off at 2-3cm above the ground. Leaving the middle leaves allowed for another crop to be harvested at a later date and to get a measure of the differences between the various soil treatments over time. Plots were harvested one at a time and leaves from individual plants within each plot washed, dried, measured and weighed separately. The longest and broadest leaves from each plant were measured.

Turnips were harvested 133 days after planting, although under ideal conditions the time from sowing seed to harvest is estimated at 50 days from time of sowing (Gilbert and Hadfield, 1996). Long growing times again contributed to cool temperatures during winter. All turnips were harvested, weighed and measured according to the following method:
All turnips were pulled, washed and allowed to dry. Each plant was weighed including leaves. The leaves were then chopped off and the root weighed separately. The maximum diameter and maximum length of the root was also measured.

The cabbages were harvested 175 days after sowing and 123 days after planting. The estimated growing time under ideal conditions is 120 days (Gilbert and Hadfield, 1996). All cabbages were harvested and weighed according to the described method:
Plants were cut off at approximately 5cm above the ground. The entire plant was weighed. The head was then removed, weighed and its length and circumference measured.

Measurements of cabbage and Swiss chard plants were used to calculate an average plant index, taking into account height and diameters of plants. During harvesting, weight was also worked into the equation. Indices were weighted to fall into the same orders of magnitude for all occasions and thus give a figure which indicates growth relative to the other soil treatments over time.

7.3 RESULTS AND DISCUSSION

Results of the site soil analysis are presented in Table 7.2.

Table 7.2: Results of Soil Analyses

Parameter		Value
Soil		Sand
pH (KCl)		4.5
Resistance (Ω)		1350
N (cmol/kg)		1.45
P (mg/kg)		6
K (mg/kg)		306
Exchangeable Cations (mg/kg)	Na	24
	K	306
	Ca	927
	Mg	213
Cu (mg/kg)		1.40
Zn (mg/kg)		5.7
Mn(mg/kg)		10.4
B(mg/kg)		0.64
S (mg/kg)		10.59
C (%)		3.13
Fe (mg/kg)		58.13
Base Saturation	Na (%)	1.21
	K (%)	8.97
	Ca (%)	53.11
	Mg(%)	20.08
	T-Value (cmol/kg)	8.72

It is clear from the above results that this was a sandy soil with a low organic content, a low pH at 4.5 and low phosphorous levels. No nitrogen analysis was done in the soil test.

7.3.1 Swiss chard

Figure 7.5 shows that initially Swiss chard plants in the plot treated with algae were larger relative to those of the control, the fertiliser, and the algae-fertiliser plots. The algae-fertiliser plot had the second highest growth rate followed by the plot treated with fertiliser only. A similar pattern existed after 8 weeks where the algae plot had

Control Algae and Fertilizer Fertilizer Algae

Figure 7.4: Differences in size of spinach plants from each plot after 8 weeks.

the largest plants (Figure 7.4). The difference between the algae plot and the algae-fertiliser plot was however reduced in comparison to the first measurements. The difference in size of plants in the control plot and the other three plots was greater after 8 weeks than after 4 weeks (Figure 7.4).

At the first harvest, the yield of the algae-fertiliser treatment can be seen to be appreciably greater than all other treatments and the control plot yield had decreased relative to the yield of other plots (Figure 7.5). The second harvest, however, revealed a change in the order of productivity of the four soil treatments. Although the algae-fertiliser plot still had the highest yield, the fertiliser plot yield was the second highest, followed by algae and the control plots. The relative difference in plant yields between the three more productive plots and the control also decreased from the first harvest.

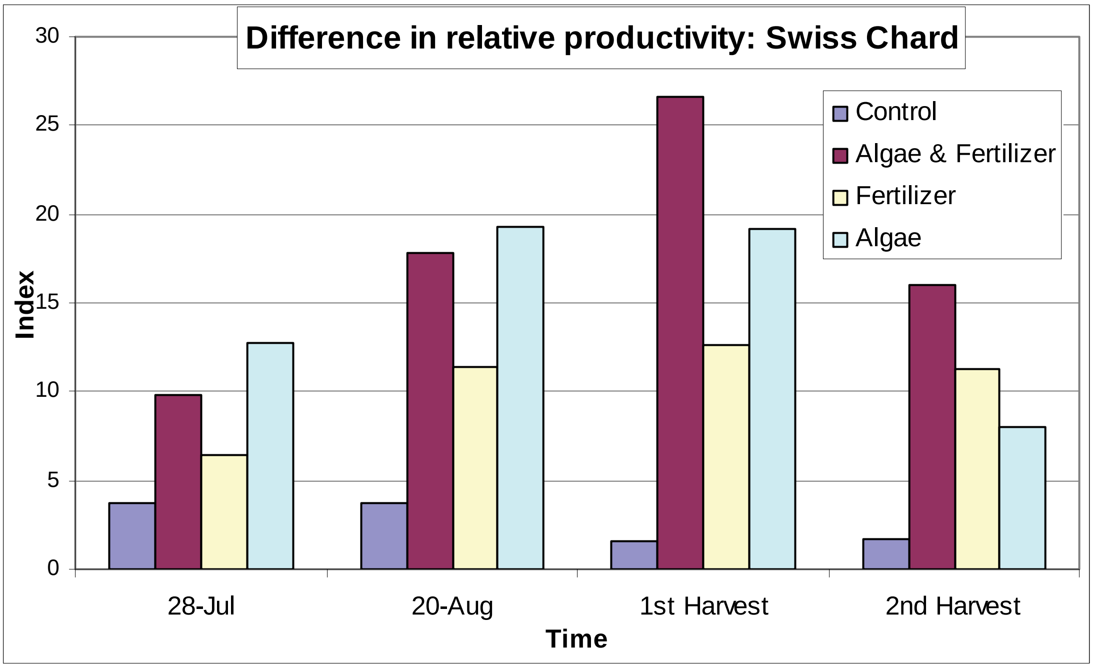


Figure 7.57: Growth rates and average plant productivity for the soil treatments relative to one another over time.

Absolute growth rates and yields are not shown in Figure 7.5. Average yields per plot over the two Swiss chard harvests are shown in Figure 7.6. The yield of the second harvest was higher than that of the first, contrary to what was expected from decreasing amounts of nutrient availability over time. Figure 7.6 shows clearly that for the first harvest, the average yield in the algae-2:3:2 plot was significantly higher at 490.7 g/plant in comparison to 385.7 g/plant for algae, 295.7g /plant for fertiliser and 83.3g/plant for the control. Standard deviations were, however, also highest for the two plots with highest yields and lowest for the control.

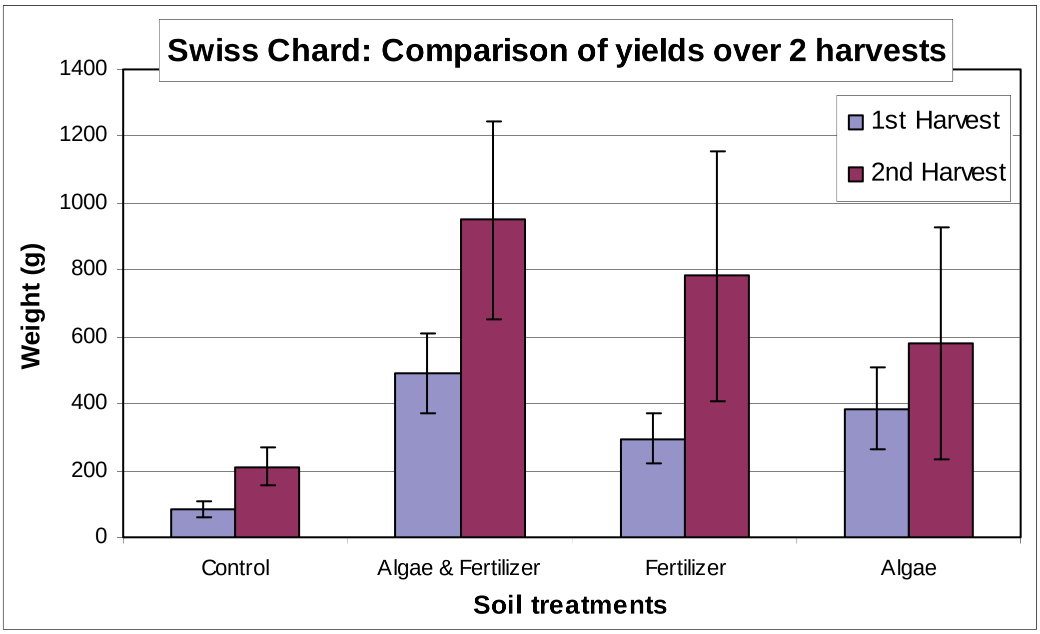


Figure 7.6: Comparison of average yields for the first and second Swiss chard harvest.

The increased yield for the second harvest is also shown clearly in Figure 7.6, with the average weight per plant at 949.3 g/plant for algae-fertiliser , followed by 781.9g/plant for the 2:3:2 plot. The plot treated with algae yielded an average of 578.6g/plant, one and a half times that of the first harvest, but now notably less than those of the fertiliser plot. The increase shown in the yield from the first to the second harvest can be accounted for by the change in season from winter to summer and therefore relative yields among the treatments must be examined. Addition of 2:3:2 increased yield for the first harvest by a factor of three compared to algae which increased yield by a factor of 5. However 2:3:2 outperformed the algae for the second harvest. The algae+2:3:2 plot yielded 4.5 times the weight of the control, 1.2 times the yield of fertiliser plot and the 1.5 times that of the algae plot.

Table 7.3: Swiss chard yield.

Yield per tons/hectare	**Control**	**Algae & 2:3:2**	2:3:2	**Algae**
Harvest 1	3.146	18.536	10.514	15.427
Harvest 2	8.005	35.864	27.802	23. 145

Differences between the four soil treatments as well as the changes in growth rate over time are most easily seen in the Swiss chard (Figure 7.5). Possible reasons for the rapid initial growth in the algae plot have been described above. The slower initial growth of the algae+2:3:2 plot cannot be explained from this experiment. Depressed growth rates due to nitrate toxicity (Chen *et al*, 2004) does not fully explain the growth of the Swiss chard as at the first harvest, the algae+2:3:2 plot produced the highest yield and continued to have the highest yield at the second harvest. Higher yield in the 2:3:2 plot in comparison to the algae plot for the second harvest could be due to a more rapid decrease in the fertiliser value of the algae than the 2:3:2 . This is in contradiction to Mulbry *et al's* (2004) findings which stated that only 3% of the algal nitrogen (N) and 60% of algal phosphorus (P) was present as plant-available N and P at the beginning of the experiment, but approximately 30% of algal nitrogen (N) and 80% of algal P was converted to plant-available N and P within 21 days at 25°C. Higher standard deviation in the two higher yielding plots may be attributed to higher competition for space, nutrients and water between individual plants within a plot as plots were larger and therefore more crowded. Another explanation could be nutrient distribution due to variability of nutritional value of the algae itself as has been observed for animal manuring (Muñoz *et al*, 2004). Increased growth rate and yield of the Swiss chard from the first to the second harvest may be accounted for by the change in season from winter to spring with accompanying higher temperatures and longer light hours (Table 7.3).

According to the KwaZulu-Natal Department of Agriculture and Environmental Affairs, Swiss chard yields of 40 tons and more per hectare can be obtained, but normally yields vary between 20 and 30 tons. Although plant spacing and plot design was not optimised for high yield, the second harvest from the algae+2:3:2 plot compares favourably to this at 35.9 tonnes/hectare.

7.3.2 Cabbages

As with the Swiss chard, cabbages in the plot treated with algae showed a rapid initial growth, far greater than the algae-fertiliser or the fertiliser plot. These differences are visible in the photographs (Figure 7.7) as well as indicated by the indices in Figure 7.8.

Control Algae and Fertilizer Fertilizer Algae

Figure 7.7: Differences in size of cabbage plants from each plot – 4 weeks (28 July).

A pattern similar to the Swiss chard can be seen in the different cabbage plots. The change in the cabbage growth rate can, however, be seen at the second measuring where the algae-fertiliser plot has an average plant index higher than that of the algae plot. The control shows comparatively slow growth on both dates with the greater difference visible at the second measurement (Figure 7.8).

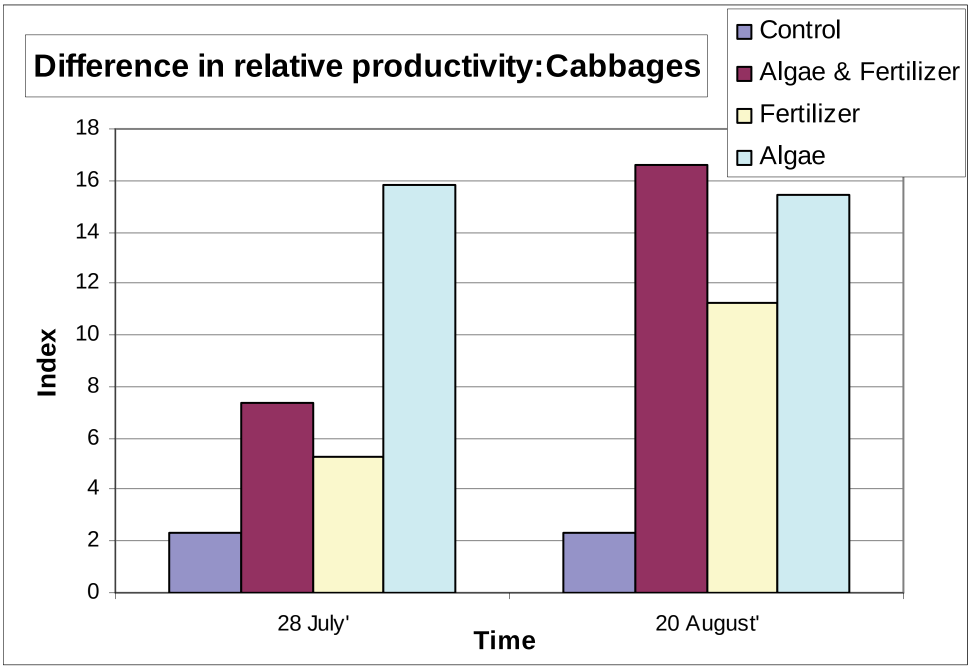


Figure 7.8: Growth rates and average plant productivity for cabbages for the soil treatments relative to one another over time.

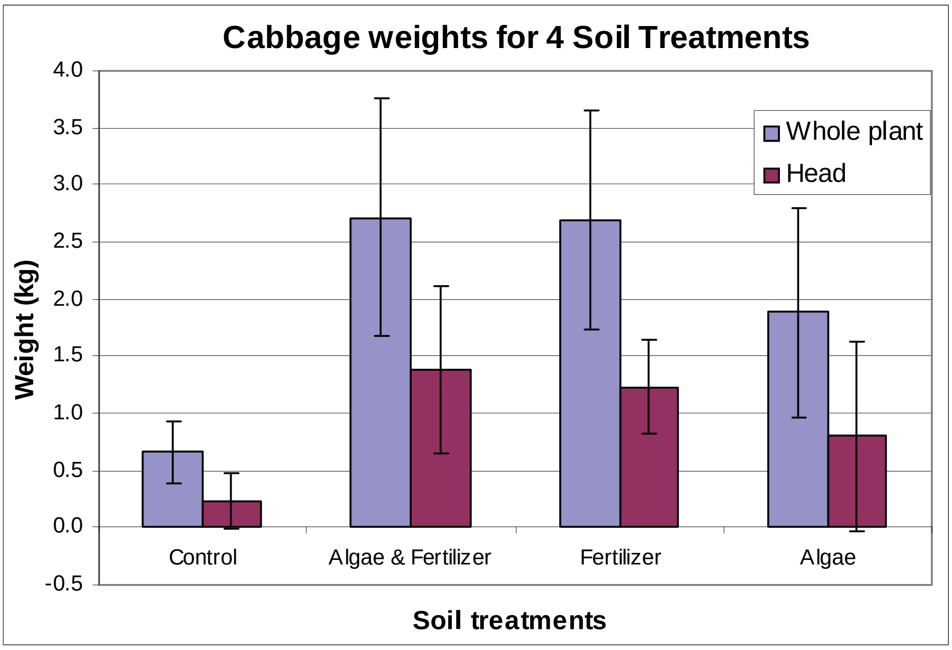


Figure 7.9: Harvest weights for the whole cabbage and the cabbage head**.**

Due to the difference in weighing and measuring methods at harvesting, a comparative plant index could not be accurately calculated as was done for the cabbages. Figure 7.9 shows the actual weight of whole plants and heads at harvest. The average weights of the whole plants of the algae+2:3:2 and the 2:3:2 plots are almost equal. The average weight of the heads was, however greater for the algae+2:3:2 plot in comparison to the 2:3:2. It is interesting to note that the average weights of whole plants and heads for the fertiliser plot were notably greater than those of the algae plot despite initial slower growth. The difference in weight of the head in comparison to the rest of the plant was smallest in the control followed by the algae plot, with the greatest difference in the algae+2:3:2. Standard deviations for cabbage heads are lower for the 2:3:2 plot than the algae-fertiliser and the algae plots, and lowest for the control plot.

Table 7.4 below gives the marketable yield in tonnes per hectare. Treatment with a single application of 2:3:2 gives an increase in yield of 6 times that of untreated soil (control) and treatment of soil with a combination of algae and 2:3:2 gives a further 4 tonnes per hectare. A single treatment with algae gives almost 4 times the yield of untreated soil despite a third of the plants in the algae plot bolting and producing no heads at all.

Table 7.4. Marketable cabbage yield**.**

Yield ton/Ha	**Control**	**Algae &** 2:3:2	2:3:2	**Algae**
Heads	5.511	36.889	32.933	21.400

Bolting was noticed in all plots but was most noticeable in the algae plot where bolting first occurred, and 4 out of the 12 plants were fully bolted at the time of harvest. Bolting also occurred in the algae+2:3:2 plot where 1 cabbage had fully bolted and one was beginning to flower at time of harvest. The 2:3:2 plot had 2 partially bolted plants and the control plot had 1 cabbage showing the first signs of bolting at harvest. Bolted plants were not taken into account on calculating average weight of heads in a plot.

Cabbages became infested with cabbage moths (diamond back/coddling moth/false coddling moth) shortly before harvesting. A difference in infestation levels was noticed between different treatments with the cabbages in the 2:3:2 plot most affected.

Initial measurements and observations showed that cabbage growth in the algae plot was notably faster than other plots and was even more pronounced than with the Swiss chard. This did not persist for as long with Swiss chard (Figure 7.5) perhaps due to cabbage's high nutritional requirements (Gilbert and Hadfield, 1996). By the second measurement plants in the algae+2:3:2 plot were larger. By harvest, 2:3:2 -fertilised cabbages were of a similar size to those of the algae+2:3:2 plot but heads were smaller (Figure 7.9). This slower but more consistent growth could be due to slower release of the 2:3:2 in comparison to the algae. Standard deviation is lowest in the control plot and due to the lowest number of developed heads measured. Once again, the high standard deviation for algae in comparison to 2:3:2 could be due to uneven spread of nutrients within the algae and or difficulty in applying exact quantities evenly across the plot. 2:3:2 plot cabbages also had the largest proportions of non-utilisable plant mass (subsidiary leaves) which constitutes wasted effort in terms of agricultural productivity. Reasons for this could not be determined from this study.

Most literature attributes bolting of brassicas to change in season, lengthening days and warming temperatures, especially if the Spring is hot (Farris, 2002; Miller and Miller, 2000, Pressman and Shaked, 1988). The proliferation of bolting in the algae plot in comparison to the other plots is explained by Mattern (1994) who states that bigger starts have a greater chance of bolting and going to seed before they reach maturity, especially if temperatures fluctuate a lot during Spring. Some brassica cultivars have a higher tendency to bolt (Pressman and Shaked, 1988) and it has been suggested that the Cape Spitz cultivar is a fast-bolter (Hart, pers. com.)

Despite problems of bolting and not optimising spacing within plots, comparatively good yields were achieved as the KwaZulu-Natal Department of Agriculture and Environmental Affairs estimate yields of curds (heads), excluding the protective leaves, generally average 10 to 15 tons for early maturing varieties and 15 to 20 tons for later varieties. Good crops may yield 50% higher.

Although not evident from the data, anecdotal comment suggests that cabbages in the two plots treated with algae were more resistant to disease and pest infestations, which could have affected weights of heads at harvest. It is generally known that healthier plants are more resistant to pests and diseases but more investigations into this aspect would have to be conducted before a conclusive statement can be made in this regard.

7.3.3 Turnips

As measurement of turnips was not possible prior to harvest, no plant index was calculated for turnips. Early photographs (Figure 7.10) reflect the trends of Figure 7.11.

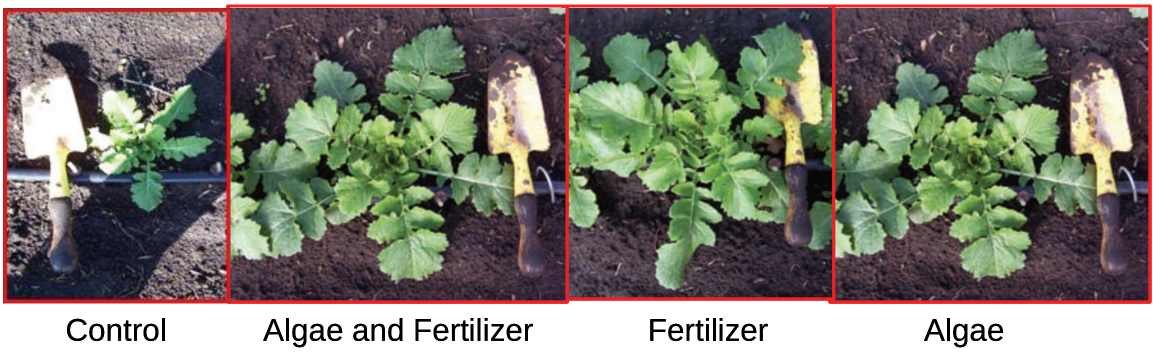


Figure 7.10: Differences in size of turnip plants from each plot – 21 August.

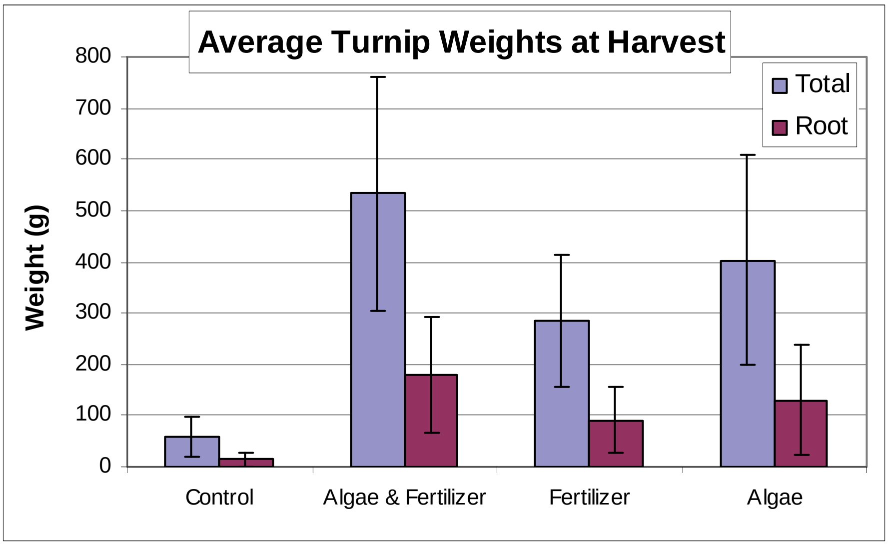


Figure 7.11: Average weight of whole turnip plants and turnip roots at time of harvest.

The whole plant was measured to compare the leaf production to root production as overfeeding, particularly with Nitrogen, can cause luxuriant leaf growth at the expense of the root crop (Hartemink *et al*, 2000). It was for this reason that the weight of the whole plant and the root crop were measured (Figure 7.11). The pattern shown in Figure 7.11 is similar to that of the first harvest of Swiss chard and cabbages with the algae+2:3:2 plot producing the largest yield followed by the algae plot, the 2:3:2 and the control plots respectively (Figure 7.12).

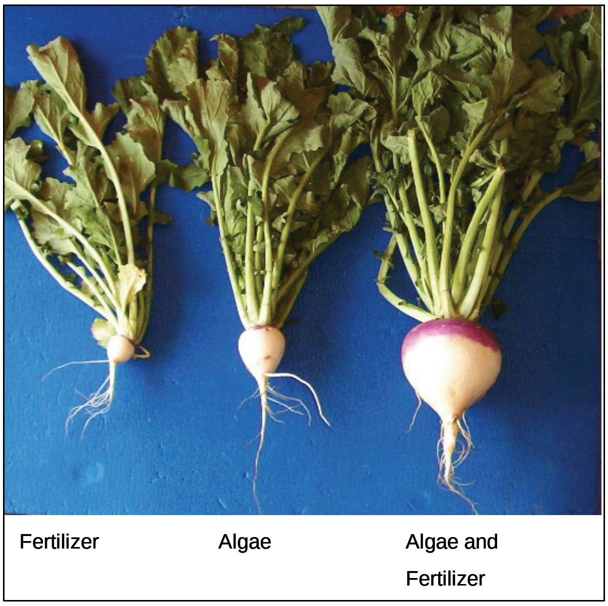


Figure 7.12. Differences between average plant size for the fertiliser, algae and algae-fertiliser plot can be seen in this photograph.

Leaves from the algae+2:3:2, 2:3:2, and the algae plots make up between 66, 68 and 67% of total weight respectively. Leaves from the control plot made up 76% of total plant weight as roots had not developed fully. As with the cabbage harvest, highest standard deviations for turnips are for the algae-fertiliser and algae plots with the lowest standard deviation for the control plot.

Although the differences in yields between the three treated turnip plots are not as dramatic as for the Swiss chard and the cabbages, the difference in weight at harvest between the control and the other plots is greatest for turnips (Table 7.5). Turnip yields once again show that the combination of algae and 2:3:2 produced an appreciably larger yield than the other treatments. As with the first Swiss chard harvest, algae produced the second highest turnip yield, more than a tonne greater than the 2:3:2 plot.

Table 7.5. Marketable turnip yield.

Yield ton/Ha	**Control**	**Algae & 2:3:2**	2:3:2	**Algae**
Heads	0.410	5.209	2.622	3.769

Overall, plots showed that addition of algae to poor soil increases plant yield in comparison to untreated soils. Algae also induced higher initial plant growth rates in comparison to fertiliser and untreated soils. Interestingly, these rapid initial growth rates did not appear in plots treated with both algae and 2:3:2. This indicates some interaction between the algae and the 2:3:2 or perhaps an overfeeding of seedlings which may initially have been toxic and slowed growth. There was little evidence found in the literature confirming that over-fertilising causes significant growth inhibition. Chen *et al* (2004) did show that plants supplied with excessive amounts of nitrates exhibited toxicity symptoms and depressed growth. Further investigations would have to be carried out to establish reasons. The slight differences between individual crop responses to the four soil conditions will be discussed separately.

The rapid initial growth rates seen in all plots treated with algae could be due to two factors, or a combination of both: Firstly, the presence of particular plant auxins, gibberellins, cytokinins, other hormones or compounds (Borowitzka, 1988; Metting, 1988; Zhang and Schmit, 2000; Zhang and Ervin, 2004; Nardi *et al*, 2004) in the freshly harvested algae could have initially promoted growth. The concentration of these 'growth promoters' would probably decrease naturally over time due to plant uptake and/or as algae died or dried out and became photosynthetically inactive. The second explanation to the rapid initial growth rate of plants in soil treated with algae only, is the bioavailability of nutrients, carbohydrates and vitamins (Mulbry *et al*, 2004; Sikoro *et al*, 2002; Borowitzka, 1988) released by the algal biomass when it was added to the soil. Again a natural decrease of these compounds over time may result in a drop in growth rate.

Root crops such as turnips have higher phosphate requirements than nitrogen requirements (Hadfield and Gilbert, 1996). Too much nitrogen causes excessive top growth (Hartemink *et al*, 2000) and it was therefore important to test the effect of algae on the growth of a root crop and examine the possibility that leaf growth would occur at the expense of root development. Comparing weights of leaves as a percentage of total plant weight showed that the three treated plots were similar (Figure 7.11) to the control plot with the highest percentage of weight from the leaves. As mentioned earlier, this was probably due to a considerably slower growth rate than the other plots and the roots had not developed adequately. No statistics could be found for South Africa but good yields are considered to be12.5 tons/bunched or 25 tons/topped per hectare in the United States (Duke, 1983). Yields shown in Figure 7.11 are not comparable to this with the highest yield at 5 tonnes (metric)/ha. Plant spacing and plot size would have to be optimised before comparisons could be meaningful for large-scale systems.

7.4 CONCLUSIONS

The following conclusions can be drawn from the field trials:

1. Algal biomass produced from the Integrated Algal Ponding System can be successfully harvested and used as a soil amendment at the garden plot scale.
2. The use of IAPS algal biomass applied directly to soil as an amendment significantly increases crop yields of cabbage, turnip and Swiss chard compared to untreated soil ($p>0.05$).
3. These increases in crop yield are greater than increases seen from the use of 2:3:2 under field conditions.
4. Under field conditions, algal biomass used in combination with 2:3:2 produces larger yields than either algae or 2:3:2 alone.
5. It is also shown that algal biomass produces more rapid initial growth rates in plants than inorganic 2:3:2 and the algae+2:3:2 combination.
6. From observation, it appears from this study that plants growing in soil treated with algal biomass from the IAPS are more resistant to pests and disease. A more detailed study would need to be carried out to confirm this observation.

8 INTEGRATED WASTEWATER RESOURCE RECOVERY: CASE STUDY

8.1 INTRODUCTION

The Integrated Algal Ponding System has been studied at the pilot and demonstration scale for more than 9 years at EBRU, and it has been shown to treat domestic wastewater effectively and achieve a high quality effluent which meets the DWAF standards for release into a water course (Rose *et al*, 2002). But over and above achieving COD and nutrient standards, the IAPS configuration, as well as the IHRAP as a stand-alone tertiary treatment unit, has also been shown to achieve high levels of disinfection of final effluent without the use of conventional chemical disinfection methods (Wells, 2005). The high quality of the effluent in terms of nutrient status and disinfection means that effluent from the IHRAP could be reused for activities such as horticulture, agriculture and aquaculture. In addition to utilisation of the effluent, algal biomass generated in the system has been demonstrated in the above studies to be a valuable plant nutrient resource comparable to commercial inorganic fertiliser.

These observations led to the consideration of IHRAP as technologies underpinning the development of the Integrated Wastewater Resource Recovery Systems concept. This simply stated, proposes that with the high quality of the treated water and the recovery of nutrient values in the form of algal biomass, these resources may be used together to provide inputs for horticultural production, value-adding employment creation and thus deliver long-term sustainability in low-cost sanitation. It was apparent that the initial laboratory- and field-scale studies reported above would need to be expanded to appropriately demonstrate the concept. The opportunity to investigate the system further arose with an award by the United Nations Environment Programme's (UNEP) and particularly the West Indian Ocean Land Based Activities (Wio-LaB) Initiative.

In the context of the poor state of wastewater treatment works infrastructure, performance and operation in South Africa and possibly in the rest of Southern and East Africa, awarded by UNEP to initiate a demonstration project for the roll-out of IHRAP technology, and granted under the WIO-LaB initiative. The WIO-LaB Project represents a strong partnership between the participating countries, the Norwegian government, UNEP, and the Global Environment Facility (GEF), focuses on addressing land-based sources of pollution that have adverse impacts on the region's rivers, estuaries and coastal waters, as well as their biological resources (www.wio-lab.org). Thus a project was initiated to investigate and plan implementation of IHRAP technology at the Bushman's River Sewage Works, with the associated objectives of horticultural utilisation of the high quality effluent and algal biomass produced. The combined targets of prevention of pollution with poverty alleviation fitted well within the overall objectives of WIO-LaB.

The rationale of the proposal is that the difference between this and other poverty alleviation schemes is that a wastewater treatment plant is an essential prerequisite for sustainability and environmental health in any community. In addition, capital and operational costs have to be covered by the government. In the case of South Africa, this is the responsibility of the local municipality, through the Integrated Development

Plan (IDP) (Madlavu, pers. comm., 2005). Within this scenario, the potential exists where algae are produced as a by-product of an IHRAP treatment works. Thus after initial training on the possible uses of the algae, entrepreneurial community members could develop sewage treatment by-product beneficiation into a business. Depending on the level of beneficiation of the algal product, vegetable gardens could be used to feed the community, vegetables could be grown for commercial purposes, horticultural businesses could be set up for the lucrative cut-flower industry or foliar feeds could be manufactured for the agricultural and horticultural industry (Horan and Horan, 2004). High quality effluent could be used for irrigation or aquaculture purposes. Thus the IHRAP as the chosen technology could increase the overall sustainability of a small community as well as the financial sustainability of the operation of IHRAP. It also adds to the ecological sustainability by returning nutrients to the soil, from where plants take their nutrients, thus effectively closing the nutrient cycle.

Given that the technology has widespread potential application in WIO-LaB countries, the IHRAP plant to be constructed at the Bushman's River Mouth sewage treatment ponds would be able to be used as a demonstration plant for other countries and lessons learned would be able to strengthen regional capacity for sustainable, less polluting development.

8.2 AIMS AND OBJECTIVES

The broad objective of the WIO-LaB project is the protection of the marine environment from poorly-treated domestic wastewater and by means of downstream beneficiation, to simultaneously enhance the socio-economic development of local communities in South Africa. The project had a number of immediate objectives related to the establishment and evaluation of a demonstration IHRAP facility, assessment of the potential importance of beneficiation initiatives for local communities and training of local communities in the operation of the IHRAP as well as downstream value-adding opportunities. The immediate (outcome-based) objectives were to:
Design and establish a demonstration-scale freshwater IHRAP-based facility for the tertiary treatment of effluent (freshwater) from municipal sewage treatment works and in this regard to:

1. Use the demonstration facility to inform representatives from DEAT, DWAF, local government, NGOs and the wastewater treatment sector, as well as participating West Indian Ocean (WIO) countries on the benefits and applicability of the IHRAP technology including the improved treatment of municipal wastewater, subsidising the treatment of wastewater and local/ regional economic upliftment through links with crop production
2. Build capacity in the operation of the IHRAP technology and the processing of the algal by-products in line with South Africa's economic empowerment policies aimed at previously disadvantaged groups. This includes training of local entrepreneurs and vegetable growers with regards to the maintenance of the ponding systems as well as the harvesting and optimal use of the algal biomass as a fertiliser for a community vegetable gardening project;

3. Evaluate alternative methods for harvesting and processing of algal biomass in the local context and demonstrate the harvesting technology considered most appropriate in the context of a developing country
4. Assess the suitability of IHRAP-generated algal biomass for use as a soil fertiliser relative to alternative products
5. Conduct an economic cost-benefit analysis of the IHRAP technology for the tertiary treatment of municipal waste waters in smaller communities.

The overall development objectives of the project encompass the creation of an integrated approach to prevention of pollution from poorly managed and rudimentary sewage treatment using IHRAP technology. This technology is suitable for tertiary treatment and disinfection and would act as a ‘firewall’ to minimise the risks of environmental degradation and the spread of water borne disease from wastewater.

8.3 BASELINE CONDITIONS

The current conditions relating to sewage treatment and release into the Bushmans’ River estuary reflects similar situations in four other estuaries in the same local municipality and could be indicative of conditions throughout coastal South Africa and other WIO-LaB countries. The attractive estuaries and safe beaches led to the development of beach resorts which initially relied on septic tank systems to cope with a largely seasonal influx of people. Resorts grew rapidly with little or no town planning and therefore often poor infrastructure. With the recent investment of The South African Reconstruction and Development Programme, which aims to eliminate informal dwellings and supply all households with hygienic sanitation, coastal towns have expanded rapidly to meet housing delivery targets and the capacity of sewage treatment works have struggled to keep pace.

Sewage treatment works such as the Bushman’s River sewage ponds were designed to handle seasonal loads significantly smaller than their current loading rate. 600 to 800 houses are set to be built in the area in the next five years, all adding to the sewage flows into the current ponds. In conjunction with overloading, neglect of infrastructure, poor operation and poor understanding of the systems have lead to a decline in treatment capacity and an increase in pollution as this undertreated effluent is discharged into the estuaries.

The seasonal nature of tourism means that unemployment is extremely high for 11 months of the year resulting in poverty and lack of food security for a large part of the population. 42% of the population in the Bushman’s River area is not economically active (Census, 2001). In this context, garden projects were set up in the area with grants from the Department of Social Development and the Independent Development Trust. While these projects have had limited success, lack of personal resources, lack of knowledge of commercial production methods as well as severe drought have kept vegetable production at subsistence level. In addition to the projects, other individuals are operating gardens to produce enough food to feed themselves under the same conditions but without any assistance from funders.

8.3.1. Site Description

The Marselle community is located on the western bank of the Bushmans River (33°40’08”S; 26°37’27”E) with the township of Marselle located approximately 3km upstream of the river mouth. (Figures 9.1-9.4).

Figure 8.1: Location of Marselle Township, Bushman’s River, South Africa.

Figure 8.2 Aerial photograph of Marselle Township, Bushman’s River (1): Current Sewage Treatment Ponds; (2) Bushman’s River (3) Effluent path to Bushman’s River estuary; (4) Marselle Township; (5) Bushman’s River Mouth Town (6) Indian Ocean.

The sewage treatment facility for this community is located adjacent to private land which has rights to use the treated water. The partially treated effluent is discharged directly into the Bushmans River. The community of Marselle is currently involved in two vegetable gardening projects which have received funding in the past but need additional support to be able to move from subsistence agriculture to producing surplus. These community gardens currently exist less than 1km to the south west of the ponds. As such, this location provides the ideal setting for the proposed project.

Figure 8.3: Location of the community gardens (a); proposed site for new ponds (b).

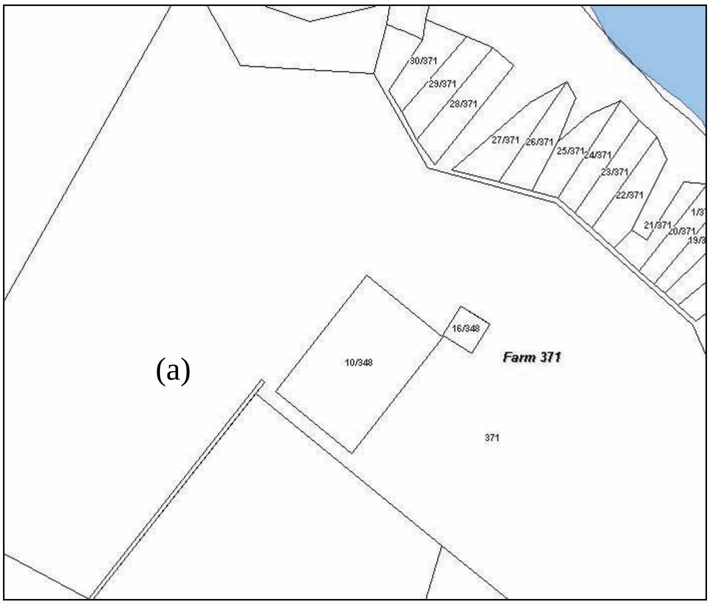


Figure 8.8: Location of Bushmans sewage ponds and land division (a).

8.3.2. Municipal structures

Marselle township and Bushman's River Mouth fall into Ward 3 of Ndlambe Municipality. Councillor Maria Mike is the Ward Councillor for this ward and as such was appointed to the project Steering Committee.

8.3.3. Ecological status

The site proposed for the IHRAP is highly degraded agricultural land with no natural vegetation cover remaining. The land is currently not in use for farming but could be used for this purpose in future if required. The current sewage ponds are known to support a variety of birdlife and small mammals such as otters. The estuary is tidal and saline for at least 20 kilometres upstream. Due to damming and over-abstraction of freshwater upstream the upper tidal reaches of the river can become hypersaline during dry spells. Natural vegetation in the area consists of coastal scrub, much of which has been cleared for agriculture and residential developments. The estuary is characterized by salt marshes established on the shallow, shifting sandbanks, an important habitat for a variety of vertebrates (including fish and birds) and invertebrates (such as crustaceans). Estuaries are also important for the health of marine fish stocks as they provide a sheltered breeding ground for marine fish.

8.3.4. Meteorological conditions

The coastal climate is mild to hot with a sporadic, predominantly summer rainfall of about 600mm/year. Average summer temperatures are between 15 and 23°C and between 11and 20°C in winter.

8.3.5. Socio-economic issues

At the last census (2001) the total population of Ward 3 was 6475 with the majority of underprivileged people living in Marselle. The Census (2001) figures put recorded unemployment rates at 30% of people of economically active age but it is suspected that this is an underestimation. Private households are the largest employer at 22% with agriculture declining to the second largest activity at 16%. Construction employed 14% in 2001 which may have risen subsequent to the housing boom. 72% of the population in the area fall into the lower quartile of annual income bracket. Pineapples and chicory are produced on a large-scale in the area, but most other crops in the area require irrigation due to frequent droughts.

8.3.6. Geology

The geology of the area is classified as arenite with areas of shale. This is evident in the steep banks of the Bushmans' River (Figure 8.5). The sediments are of nearshore marine, fluvial and aeolian origin and soils tend to be sandy (Lubke and De Moor, 1998).

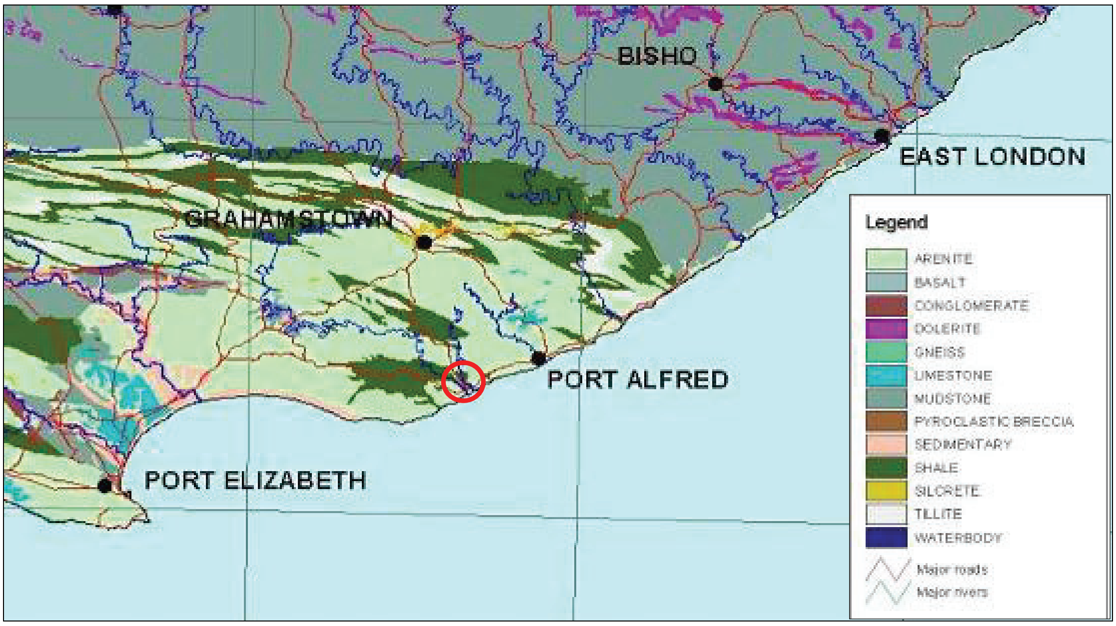


Figure 8.5: Geology of the area (Council for Geoscience**)**

8.4 DETAILED PLANT DESCRIPTION

The demonstration IHRAP plant would be constructed adjacent to the existing sewage treatment facility and would receive the partially-treated effluent from this plant. A nine year performance evaluation of the system at EBRU, Grahamstown (Wells *et al*, 2006) showed a COD removal rate of 87% and consistent residual nutrient concentrations of below 2 mg/ℓ and 5 mg/ℓ respectively (South African discharge standards are 3 mg/ℓ and 10 mg/ℓ). Under optimum conditions *E. coli* counts were reduced by 99.99%, with 78% of samples showing 100% kill (i.e. <1 cfu/100 mℓ). Under suboptimum conditions disinfection was still adequate reducing *E. coli* counts to an average of <10 cfu/100 mℓ (Wells, 2006). Although the exact size of the pilot IHRAP facility is constrained by the available budget, it is likely that the facility will be of sufficient volume to accept at least half the flow from the existing municipal facility. Should the hydraulic load increase substantially at a future date then the ponds would accept a limited proportion of the full flow or funding would need to be sourced to increase the effective volume of the IHRAP by constructing additional units. The demonstration plant will consist of two IHRAPs, and the design will be similar to that of the pilot-scale IHRAPs already in operation at the EBRU field station (Figure 8.6 & 9.7).

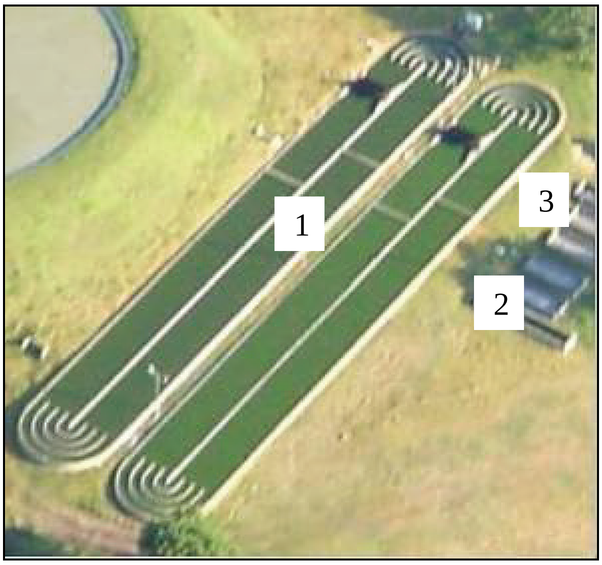


Figure 8.6: Aerial view of the High Rate Alga Ponds at the Environmental Biotechnology Research Unit field station showing High Rate Algal Ponds (1) and Algal Settling Ponds (2) and Algal Drying Beds (3).

Figure 8.7: View of an High Rate Algal Pond at the Environmental Biotechnology Research Unit field station showing the paddle wheel (1) and motor (2).

The existing Bushman's Sewage Works is a pond-based treatment system and consists of five ponds. The effluent from these ponds is currently flowing into the Bushman's River 2 km upstream of the river mouth. The current mean influent to ponds is 178.2 m^3/day which is the equivalent of 7.2 m^3/hour. Treated and disinfected water from the IHRAPs would be piped to a storage dam (6000 m^3) and from there to the vegetable gardens. Algal biomass recovered from the algal settling ponds would be collected and transferred to the gardens for fertiliser applications. The total combined area of the vegetable gardens would be 15 ha in size. Each of the two community gardens would be supplied with a single standpipe and horizontal hose for flood irrigation. The total irrigation time is estimated to be between 5 and 6 hours per day, so each project would be able to irrigate for 2.5 to 3 hours per day. During periods of sufficient rainfall irrigation time would be reduced and the treated water stored in the dam for future use. A public-private partnership would be set up with experienced farmers for mentorship in crop production methods as well as marketing and distribution of produce. Crops planted as part of the demonstration project would include cabbage, cauliflower, lettuce, beetroot, carrots, sweet potato, lentils and leeks.

Two IHRAP ponds would be constructed so as to provide both for the adequate disinfection under routine operation of the system, as well as its use as an experimental facility to provide maximum flexibility for possible further development work.

Detailed drawings of the IHRAP and paddlewheel design are presented in Figure 8.8 and 8.9. Usually the HRAP would be designed based on organic loading and solar energy. In this instance, with disinfection as the primary objective, the design parameters were hydraulic detention time (HRT) and the selected flow rate (Q). Experimental work at the field station in Grahamstown (EBRU) has shown that with an average HRT of 5 days full disinfection is achieved, thus the design of the ponds will be based on this figure. Calculations were based on figures shown in Table 8.1.

Table 8.1. The calculation of the dimensions of the Independent High Rate Algal Ponds.

Current flow rate (Q)	2 ℓ/s, = 7.2 m^3/h, or 172.8 m^3/d.
Volume/IHRAP	728m^3 each
IHRAP Depth	350mm
IHRAP Area	1040m^2 each.
IHRAP Width	16m
IHRAP Length	65m

The topography of the land would determine if the IHRAP can be gravity-fed from the existing ponds. This would be assessed by the contractor has been identified.

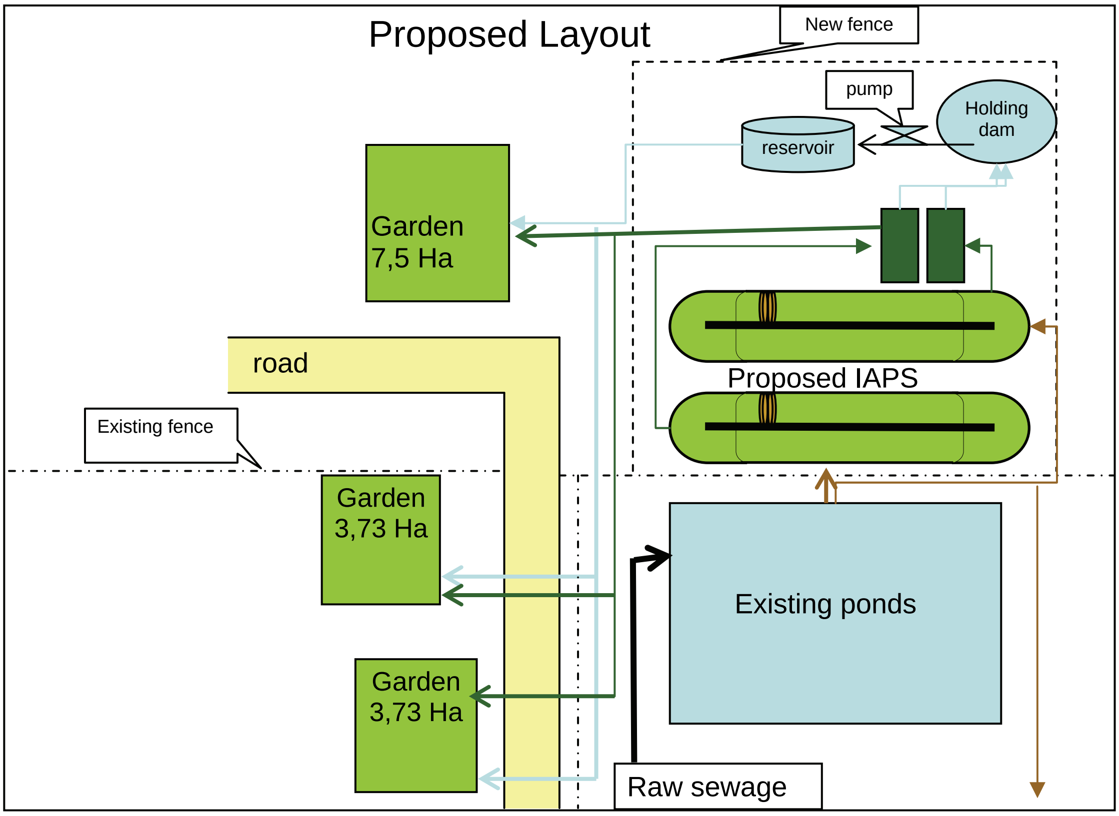
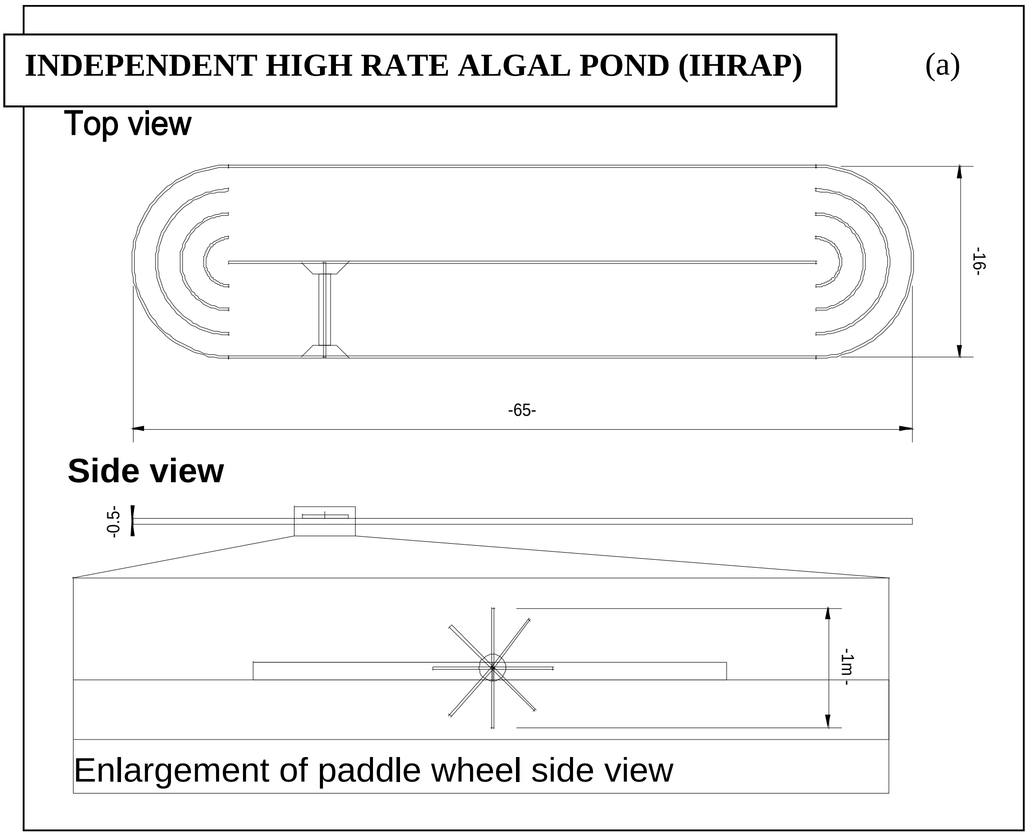
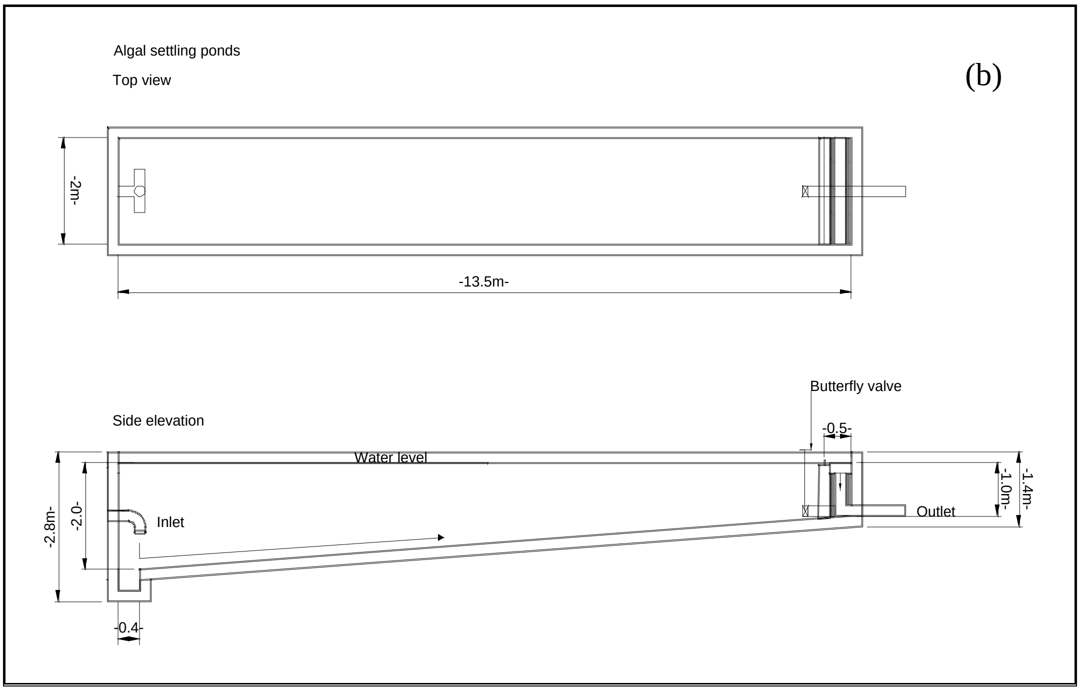


Figure 8.8 ; Proposed Layout of Independent High Rate Algal Ponds and gardens relative to existing sewage ponds at Bushmans River.





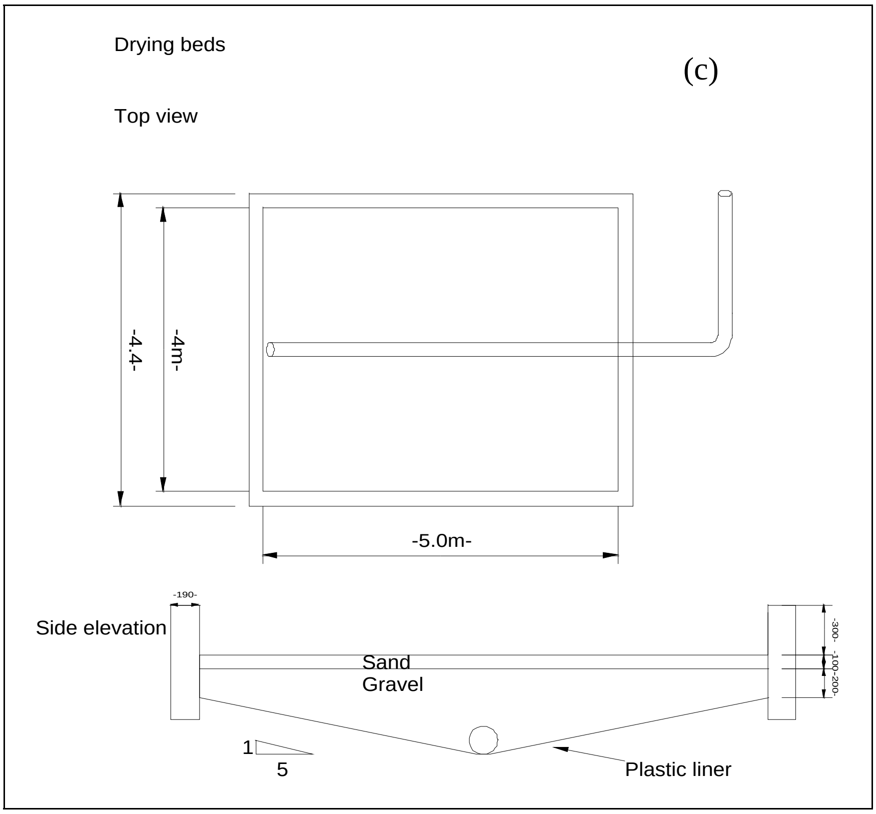


Figure 8.9 ; Plan view and cross-sectional view of algal settling ponds (a); Plan and side view of the paddle-wheel showing positioning in the Independent High Rate Algal Ponds and support structures (b); and plan and cross-sectional view of algal drying beds (c)

The IHRAP ponds would be constructed with the outer walls consisting of earthworks with 10% lime stabilisation to the top third. Ponds will be lined with clay. The centre wall will be constructed from concrete block as will the support structure for the paddlewheel. 110mm uPVC pipe will be used as well as a 110mm socket vale. A Eurodrive motor (DT71D6 V230/400; 50 Hz; 880 rpm; 0,25 kW) and gearbox (R57A; 6 speed 1400 rpm; 147.92 ratio) will be installed to turn each paddlewheel.

The estimated cost of construction for the IHRAP ponds and associated infrastructure is US$ 65 372 (2007 values). Irrigation infrastructure will be set up to convey the polished effluent from the settling ponds to adjacent cultivated land.

Risks and assumptions

Risks involved in the implementation of the IHRAP system for the tertiary treatment of the effluent from the Bushman's River sewage treatment ponds are both technological and socio-political. It is essential to identify the risks and where possible, develop and implement appropriate mitigation measures. The risks and assumptions associated as well as mitigation measures are described below.

The technological risks are considered to be minimal due to the robust design of the system and preceding research and demonstration programme. However, risks could include the breakdown of pumps, motors and the interruption of electricity to the plant. As there is only a single essential motor per pond which drives the paddle wheel, the risk of breakdown is small and the ponds are regarded as having very low-maintenance requirements. In the case of electricity supply interruption, the plant would not be able to treat the water to the necessary level required for irrigation. Under these conditions, irrigation with effluent should not occur directly from the outfall and the partially-treated effluent from the ponds would need to be returned to the influent. The key assumption related to technological risks is that the plant operators are correctly trained and that they perform the necessary duties as required. This risk is mitigated by the low skills level required to operate the IHRAP effectively.

Algal biomass accumulates metals from wastewater which is comparable to other wastewater sludges. Due to the domestic nature of the wastewater treated at the sewage ponds and the absence of heavy industry in the area, the risk that the wastewater should be contaminated with heavy metals which could potentially accumulate in the algae is low. In order to establish the validity of this assumption, elemental analysis should be conducted on the water and the algae from time to time where it is used in any agricultural applications.

Strategy for ensuring long-term sustainability

The treatment of municipal wastewater to a level that it does not pose a threat to human or environmental health is the duty of governments and their representative local authorities. As such, the long-term management of the existing sewage treatment facility and proposed ponds are the responsibility Ndlambe Municipality. However, with the potential value of the recoverables of high quality water and algal biomass, external service provision for the operation and maintenance of ponds could provide a business opportunity. The current net cost of the system could potentially be replaced by a revenue stream generated from the sale of surplus vegetables and other beneficiation products such as fertiliser and, potentially, products from aquaculture operations. 2:3:2 to the value of ZAR 120,000/year would be required to adequately fertilise 15 ha of vegetable gardens. It is estimated that the ponds will produce at least 500l per week of algal slurry. At an application rate of 500ml per m^2, this will fertilise $1000m^2$ every week. Thus, in the year the 15 hectare area can be fertilised 5 times equating to ZAR 400,000 in savings to the agricultural project. Based on the assumption that this algal biomass could be translated into fertiliser value, the ponds could generate around ZAR 400,000 per year. The cost of water in a peri-urban setting such as this would need to be considered. Municipal water in this area is charged to consumers at ZAR $5.70.kl^{-1}$. Even at half this value $172.8m^3.day^{-1}$ has the potential savings of approximately ZAR 5,000 per day or ZAR 1.8million per year. Such costs impact substantially on the sustainability of peri-urban garden projects and, where irrigation is needed, water costs have to be subsidised. Savings of over ZAR2million have been calculated without factoring in vegetable sales generated from the gardens and before any beneficiation of the algae into products such as foliar feed. This income generation can be balanced against the estimated budget of ZAR 120,000 for general maintenance of the current infrastructure.

This has not accounted for potential in the lucrative mariculture and aquaculture fields. These enterprises have the potential for the establishment of a public-private partnership to ensure sustainability. The details of such an arrangement would need to be worked out carefully but this is possibly the best model for the long-term success of such a project.

8.5 CONCLUSIONS

1. Bushman’s River Sewage Treatment Works provides an opportunity to demonstrate Integrated Wastewater Treatment and Resource Recovery in the form of treated effluent and algal biomass
2. The long term sustainability of a sewage works which incorporates integrated wastewater resource management could be achieved through public-private partnerships. Under careful management sewage works could become income generating facilities
3. A demonstration plant would allow for an effective evaluation of the integrated approach to the improvement of the sewage effluent’s environmental impacts and linkage to social upliftment. The proposed project would be showcased to key role players at international as well as local level including national government departments, regional and local government as well as private sector participants in wastewater treatment.

9 CONCLUSIONS

Studies reported here (Appendix I) and elsewhere have shown that a substantial number of sewage treatment works throughout the Eastern Cape Province and South African are in need of intervention to prevent severe health and environmental impacts. Lack of management, operator skills, functioning infrastructure, maintenance and support knowledge are cited as the main causes of poor performance. From the nutrient status and disinfection levels of monitored effluent, it can be concluded that effluent quality and therefore treatment efficiency is not consistent and is generally inadequate and poses a threat to the health of the environment and the surrounding communities.

Due to the relatively small size of many of the facilities in the region, it is proposed that the IHRAP technology developed for tertiary treatment (including disinfection) in small STWs be considered for the reduction of pathogen load in the effluent prior to discharge. Furthermore, use of robust and inexpensive IHRAP technology to address the sanitation needs of smaller communities could simultaneously contribute to local economic upliftment through the recovery and use of treated water and the algal biomass by-product in horticultural production.

IAPS and IHRAP have been demonstrated to achieve a high level of disinfection without the use of chemical treatment such as chlorination or ozonation. Levels of disinfection from <1-10CFU/100 mℓ are achieved and substantially exceed the DWAF general standard of disinfection of 1000CFU/100 mℓ required for irrigation use of treated effluent. This makes it possible to re-use the effluent for activities such as irrigation without further treatment. Proven as a robust technology which does not require high operator skill levels, the IHRAP can be seen as an appropriate technology for small sewage works. The low cost, adaptability and high quality effluent means retrofitting of IHRAPs in particular can provide an immediate intervention to provide a 'firewall' between poorly performing sewage works and the receiving environment. Such interventions are critical in the prevention of pollution and, importantly, in the prevention of the spread of disease. This is crucially important in the current situation with large numbers of immuno-compromised people at risk in southern Africa.

The potential for treated wastewater re-use and the beneficiation of microalgae grown on domestic wastewater and applied in horticultural applications has been recognised in the literature. It is apparent that the IHRAP technology provides an enabling potential for linking of sustainable sanitation and horticulture as well as poverty alleviation on a practical level. The growth stimulating properties of algae, while well known for seaweeds, was relatively unexplored for microalgae such as grown on the IAPS. Experimental work showed that algal biomass can be recovered from an IHRAP treating domestic sewage and utilised as a soil amendment in horticulture or agriculture. Results of the laboratory and field trials into algal biomass soil amendment revealed that algal biomass as a soil amendment can significantly enhance plant growth, equal to that of the commercial inorganic fertiliser 2:3:2 (N:P:K). A recovery value of approximately ZAR 150,000/ha.year has been estimated for the Bushman's River System reported here.

Macroalgae (seaweeds) contain growth hormones such as cytokinins, auxins, indoles and gibberellins as well as chelating agents and micronutrients and is used in the manufacture of foliar feeds. Although microalgae also contain these, they appear not to have been used in foliar feed production. The potential therefore exists to manufacture foliar feed from the algal biomass. While initial studies were inconclusive but it is felt that further investigation is needed in this area to fully explore the possibilities of microalgae-based foliar feed development.

An investigation of the feasibility of the integrated approach to wastewater treatment incorporating the IHRAP as a retrofitted tertiary treatment system and resource recovery mechanism was conducted for small sewage treatment works. An application of the system was investigated as a case study at Bushman's River in the Eastern Cape. In addition to the immediate health and environmental benefits of disinfection and improved effluent quality, additional benefits such as entrepreneurial opportunities in horticulture, agriculture and mariculture, and therefore self-sufficiency or even the profitability of a sewage treatment works has been explored in this study.

Urban development has placed substantial pressure on water resources, particularly in coastal areas, where the pace of development has been more rapid than the ability of service delivery to keep up. Potable water in these areas is often supplied at high cost, and some coastal areas are increasingly forced rely on reverse osmosis for all water supply purposes, including sewerage reticulation. The integrated wastewater and resource recovery concept investigates the recovery of some of these costs in the form of algal biomass directly, through public-private partnerships, or indirectly through job creation and entrepreneurial opportunities.

9.1 RECOMMENDATIONS

Based on the above study, a provisional feasibility for the Integrated Wastewater Resource Recovery System based on IHRAP has been demonstrated for the small sewage works. The laboratory studies of algal biomass utilisation and the Bushman's River case study provide the baseline for follow-up investigations. It is thus recommended that sufficient information is now available to undertake further studies at a demonstration scale for the concept. These include the following:

1. It is recommended that a demonstration plant comparable to the Bushman's River case study be constructed to subject the concept to a detailed and rigorous investigation
2. A detailed economic study into all aspects of the integrated wastewater resource recovery concept demonstration is needed in order to gain support and confidence within the political and sanitation sectors to roll out similar designs in the developing world
3. Further studies into the plant hormones and nutrient content of the algal biomass are needed to fully understand the mechanisms behind the growth stimulation of the algal biomass when utilised as a soil amendment
4. Refined techniques of IAPS algal foliar feed production need to be developed and tested to ascertain the viability of creating a high value foliar feed product equivalent to successful kelp-based products currently on the market.

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11 APPENDIX I: THE STATUS OF SEWAGE TREATMENT PLANTS IN THE EASTERN CAPE PROVINCE

S.J. Horan, K.J. Whittington-Jones, N.G. Mohale and P.D. Rose

11.1 SEWAGE WORKS IN SOUTH AFRICA

Work conducted, but as yet unpublished, by Antrobus in 2002 and Whittington-Jones *et al* in 2003 focused on the state of sewage treatment works in the Eastern Cape. A subsequent study was published by Snyman *et al* (2006) which indicated that the Eastern Cape situation reflected the wider South African experience. Despite sanitation remaining high on the government agenda over the time period from the 2002 study, the problems of operation, maintenance and skills shortages identified, particularly for small sewage works, remains barely unchanged (Antrobus, 2002; Whittington-Jones *et al*, 2003; Snyman *et al*, 2006). These studies provide an indication of the problems that are experienced and require attention in the developing world context. The main findings of Snyman *et al* (2006) are outlined below.

Snyman *et al* (2006) conducted a limited national survey of 51 STWs ranging from micro (<500 $m^3.d^{-1}$), small (500 $m^3.d^{-1}$ to 2-10 $M\ell.d^{-1}$) to medium (2-10 $M\ \ell.d^{-1}$) using different treatment technologies. In this study it was found that only 4% of the surveyed works complied with DWAF general standards. It was also found that immediate intervention was required for about 30% of surveyed works to avoid crisis situations such as an outbreak of waterborne diseases, and a further 66% required intervention in the short to medium term (Snyman *et al*, 2006). More than two thirds of surveyed STW "equipped with disinfection, or attempting to disinfect the treated wastewater" were experiencing problems. Lack of monitoring data was again highlighted as a major concern as effectiveness of chlorination could not be gauged by operational staff.

Compliance to general standards for treatment and monitoring of wastewater is clearly a major problem at the majority of STWs in South Africa and reaching crisis levels at as much as a third of sewage treatment works, not due to lack of infrastructure or poor technology, but largely due to lack of skills in operation and maintenance of existing treatment facilities (Snyman *et al*, 2006). This is a dire situation considering the growing number of immuno-compromised people in this country, the growing pressure on natural resources and the awareness of long-term impacts of continuous misuse of these resources.

11.2 SEWAGE WORKS IN THE EASTERN CAPE PROVINCE

Little is currently known of the overall picture of the STW in the Eastern Cape, although each is monitored to some degree individually. This information contrasts with increasing concern over the declining water quality of the Eastern Cape's rivers and the increasing threat of cholera in the Province since 2000 (DWAF, 2003). The recent incident (September, 2005) of outbreaks of typhoid in Delmas (Mpumalanga) was directly linked to contamination of drinking water by sewage and highlighted the importance of stringent controls, proper management, infrastructural integrity and adequate sewage treatment (Graham, 2003).

It is important to establish a clear picture of the situation in the Eastern Cape and it follows that wastewater treatment plants, as one of the sources of this pollution, should be investigated and, where feasible, mitigating and corrective measures should be implemented. This investigation was carried out by an examination of the capacities and treatment technologies, as well as nutrient and bacteriological status, of the effluent discharged from Eastern Cape sewage treatment works.

Many problems related to the management of treatment plants in the Eastern Cape are historical remnants of the previous division of the provinces and subsequent mergers of local authorities. The former Ciskei and Transkei areas were operated under different regulations and had different budget priorities to that of the pre-1994 Eastern Cape. Many problems have arisen due to lack of funding, relevant skills, interdepartmental coordination, appropriate technology and infrastructure.

11.3 METHODS

The study investigated the quality of treated effluent from STWs in the Eastern Cape Province, South Africa, (Figure A.1) for the period January 2002 to May 2003. All data concerning STWs in this study were obtained from the Department of Water Affairs and Forestry (DWAF) who in terms of National legislation, is the custodian of the water resources within South Africa. In terms of water quality monitoring, the province is divided into three regions, namely Port Elizabeth, East London and Umtata, and each regional office was approached for data concerning the STWs under their jurisdiction. Apart from a comprehensive list of all STWs in each region, the following information was requested for each facility; daily capacity (ML), technology employed and seven routinely measured analytical parameters for treated effluent [COD, pH, ortho-phosphate as phosphorus, ammonia nitrogen, suspended solids (SS), nitrate/nitrite nitrogen and faecal coliforms]. Effluent disposal methods and the dates of recent upgrades were also requested. As all analysis was conducted by municipal laboratories, a potential limitation of the research was the assumption that analysis was conducted using standard techniques for analysis of water samples.

Availability of sanitary analysis data determined the STW on which thorough nutrient and bacteriological analysis could be done. The full sanitary analysis of 14 STW in the Port Elizabeth area was obtained and analysed with respect to average nutrient values (ammonia, nitrates and nitrites, and phosphorus) as well a bacteriological counts (faecal coliforms and *E. coli*). These were compared with the general and special discharge standard as laid out by Section 21 (f) and (h) of the National Water Act (No. 36 of 1998) as well as the guidelines laid out in the Water Quality Guideline Series (DWAF, 1996).

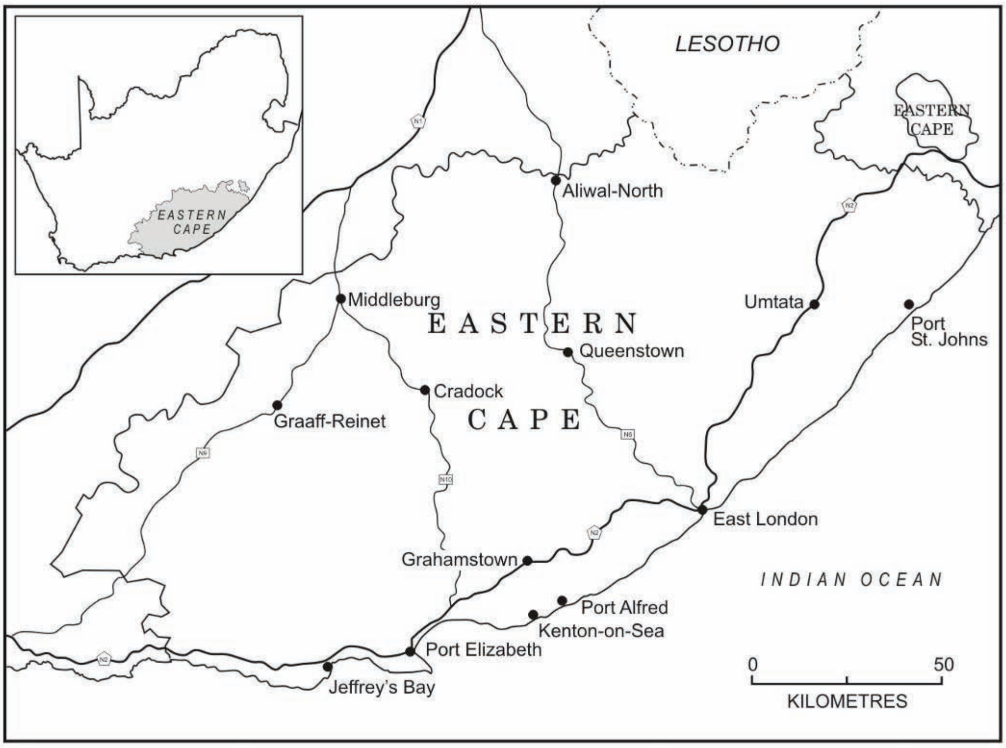


Figure A.9: A Map of the Eastern Cape showing the location of the three main cities of Port Elizabeth, East London and Umtata.

Ground truthing of data was conducted through site visits to sewage works in the Alfred Nzo and Cacadu Municipal Districts in 2003, 2005 and 2006 as well as via discussions with municipal and DWAF officials. The results of the survey conducted by A. L. Abbott and Associates as part of the Municipal Mentoring Project (Davies, 2002) were also reviewed.

11.4 RESULTS AND DISCUSSION

To date, full coordination between municipalities, which in most cases are responsible for the operation of the STW, and DWAF, which is responsible for monitoring them, has not been achieved in the Eastern Cape. Although the three regional DWAF offices have most of the relevant data for their areas, no single database exists for the monitoring and recording of sewage treatment work type, capacity and sanitary analysis data. Furthermore different sources have given conflicting information for some of the works. It is also clear that not all works are listed in one of the three regional DWAF STW databases, e.g. DWAF data from the East London Office showed no recorded marine discharge in the area while another database showed that marine discharge was occurring; Rhini Ponds (a.k.a. Mayfields) in Grahamstown was not listed. Municipal STW are also required to keep records for operational purposes (Everton, 2002). Such omissions were noted during collation of data from different offices and may have arisen through merging of local authorities and redefining of municipal and provincial boundaries. These oversights serve to highlight the need for coordination between regional offices and for a single comprehensive database for the entire Eastern Cape.

11.4.1 Size distribution

According to the three regional DWAF databases, there were 189 STWs in the Eastern Cape Province with 52 in the Umtata region, 65 in the East London region and 72 within the jurisdiction of the Port Elizabeth DWAF office (Table 1). Although the design capacity information for a small proportion (5.6%) of the STWs was not available, the majority (73%) of STWs in the province had a design capacity of <1ML d-1 (Figure A.2) and were thus considered small.

Table A.12. Design capacity distribution of sewage treatment works within the Eastern Cape Province, South Africa.

	Region		
Capacity (Mℓ d-1)	Port Elizabeth	Umtata	East London
< 1	45	47	45
1-5	10	3	10
5-10	3	1	5
>10	3	1	4
Unknown	11	0	1
Total STWs	72	52	65

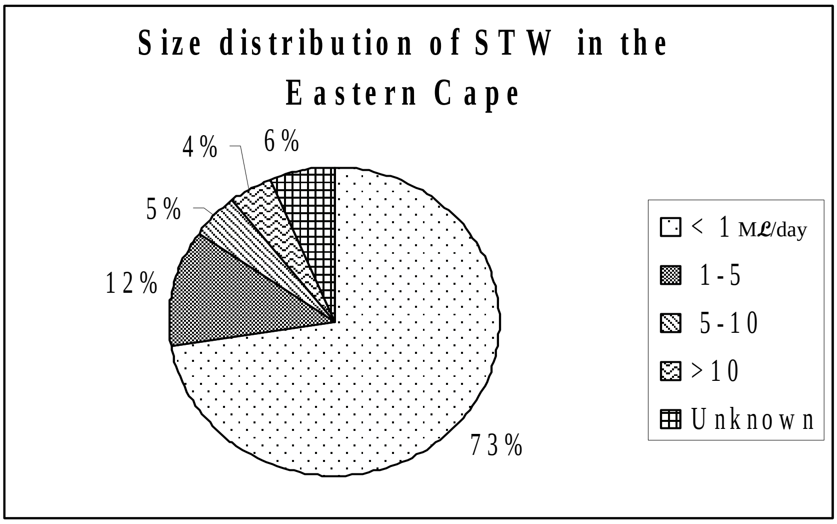


Figure A.10: Size distribution of Sewage Treatment Works in the Eastern Cape based on loading in Ml.day^{-1}.

Many STW in the Eastern Cape were still operating under permits issued in terms of the Water Act of 1956 and not the National Water Act of 1998 (Retief, pers. comm., 2002). Daily flow rates may, therefore be more or less than stated in the Permit or in the DWAF records and are not always true to the situation on the ground (Retief, pers. comm., 2002). For capacity to be monitored, all works should have functional flowmeters. Many sewage works reportedly had flowmeters, but the functional status of these was questionable. Many flowmeters have been reported to have malfunctioned but lack of funds has meant that no repair-work was undertaken (Retief, pers. comm., 2002) and months or even years have passed since flowrates were last measured at some works. This was confirmed by the Municipal Mentoring Programme survey (Davies, 2002).

The Port Elizabeth and East London areas have a more even spread of sewage works over the different size categories although in both areas over 60% are small. Many institutions, especially prisons, in the Port Elizabeth and East London areas also operate their own treatment works. In some cases this may be explained by the prisons' location, which is usually outside urban areas or in peri-urban areas and therefore outside of the main sewerage reticulation system. Many industrial activities produce relatively large quantities of wastewater, too large or of a quality not suitable for direct release to municipal wastewater treatment plants. These industries therefore treat their own effluent and have small STW with design capacities of less than 1Ml/day. These industrial STWs account for a portion of the small STWs in these two areas. The cities of East London and Port Elizabeth and the large townships surrounding them, as well as larger towns such as Grahamstown, Cradock and King William's Town, account for the number of the larger capacity works cited.

There are various economic implications in the running a large number of small STW, especially within a single municipal area. Budgets have to be divided such that funds for individual STW may be rendered inadequate. More operational and maintenance staff relative to capacity are required to run many small works. Alternatively, staff may be responsible for more than one works and have to travel between them. Although with the simpler technologies generally used in smaller works such as ponds, high skills levels are not usually required but basic maintenance is vital to ensure wastewater is treated effectively. Small and often relatively variable populations are served by small STW such as schools, universities and coastal resort towns. This gives rise to variable hydraulic and organic loads which requires adequate capacity to handle peak loading. Size and therefore budget may only provide for the employment of part-time operation, precluding the retention of highly skilled personnel (Sanitary Engineering and Public Health Handbook, 1998).

The 14 works which were analysed in detail in this study consisted of 6 works with a capacity of less than 1 Mℓ/day, 7 works receiving 1 to <5 Mℓ/day and one large works of between 5 and 10 Mℓ/day (Appendix II). This selection indicates that while the majority of STW fall into the first category, data from small works are not readily available. While full sanitary analysis is not required for small works under the NWA, required data was also unavailable. This was confirmed by Davies (2002) in the survey conducted by Abbott and Associates. No clear trend was observed between the capacity of the works and nutrient and bacterial removal efficiency, although the larger works (>1 Mℓ/day) appear to exhibit more stable operation with less variability in effluent quality.

11.4.2 Treatment Technologies

As expected from the size range of facilities, a number of different technology types are employed in the province. Difficulties were encountered with this particular aspect of the study as the descriptions of the technologies employed were often brief and, particularly in the case of ponding systems, information regarding the exact design of the ponds was often not available. Ponding (evaporative and oxidation) was the principle technology used for STW in the Eastern Cape (Table A.2). In the Umtata region 71% of STWs employed ponds as the main technology, with a slightly lower occurrence in the other regions. The majority of medium STW (capacities of 1 to <5 Ml/day) used biological treatment systems such as biofilters and activated sludge systems. Large STW (>5 Mℓ/day) all used activated sludge systems. The exact definition, design specifics and the extent to which "package plants" overlap with other technology types listed in Table A.2 are unclear, but these systems are only employed at 10% of facilities. The technology employed at 14% of the STWs in the province could not be determined from the available information.

Table A.13: Occurrence of different treatment technologies at sewage treatment works of all sizes within the Eastern Cape Province, South Africa.

	Region			
Technology Type	Port Elizabeth	Umtata	East London	Total
Ponds	25	37	34	96
Package plants	9	8	2	19
Activate sludge	14	1	18	33
Reed beds	1	0	0	1
Biofilter	7	1	5	13
PETRO	0	1	0	1
Unknown	16	4	6	26

Preferred treatment technology should depend largely on the quantity and character of effluent the treatment plant is required to handle on a daily basis as well as factors such as the availability of land, skilled workers and funding. However, current technological trends and engineering preferences often influence the selection of a particular technology to a greater degree than is ideal. No correlation between treatment technology and effluent quality was apparent, particular from the data. Influent quality, operator skill and experience, dedication as well as municipal capacity and state of infrastructure are all factors which influence the efficiency of the works apart from the technology used.

11.4.3 Performance Survey

At least some monitoring data existed on the DWAF databases for 97 of the 189 STWs (51.3%) for the chosen study period although, in some instances, data were irregular and often did not include all of the required parameters. The most regularly monitored STW was at Cradock (17 times during the study period) in the Port Elizabeth region, while at least one site in each of the 3 regions were only monitored by DWAF on a single occasion between January 2002 and May 2003 (Table A.3). However, while the data shown in Table A.3 are an accurate reflection of the frequency at which DWAF obtained information for the various STWs in the province, management of each STW or of the municipality in which the STWs were located may have undertaken additional monitoring that was not recorded on the databases used in the current study.

Table A.14: Monitoring frequency of surveyed sewage treatment works in the Eastern Cape between January 2002 and May 2003.

Region	Minimum	Maximum	Mean	SD	n
Port Elizabeth	1	17	9.02	4.7	34
Umtata	1	9	3.5	2.3	32
East London	1	12	5.5	3.1	31

The reliability (i.e. regularity of sampling) of the data provided in the sanitary analysis varied greatly within the area, and within individual S.T.W, possibly due to irregular monitoring or due to inconsistent operation which affects performance of S.T.W. Regular audits of wastewater treatment plants are required, but the responsibility of these audits lies with the local authorities, many of which are ill-equipped to do the necessary analysis and it is, therefore, not possible to perform these thoroughly or as regularly as stipulated in the legislation (Lucas, pers. comm.; Retief, pers. comm.).

A detailed examination of 14 STWs in the Port Elizabeth region was conducted in 2002. These were chosen due to the consistency of monitoring of the required parameters. None of the 14 works examined discharged final effluent into water resources listed by the NWA and therefore were not required to meet special effluent standards. However, effluents of 7 out of the 14 works were used for irrigation, mostly of farmland, and in Middelburg for the irrigation of the golf course. The effluent from the Tekroveer works (Kenton-on-Sea) and excess effluent from the Bushman’s River Mouth works was discharged into the Kariega River and the Bushman’s River estuaries respectively. Both estuaries are popular recreational and fishing areas. The issues surrounding this situation are discussed further in a later section. The use of treated wastewater for irrigation and recreation has certain impacts, restrictions and implications for the STWs and wastewater users concerned, depending on levels of nutrient and pathogen removal achieved. DWAF (1996) published a set of guidelines which laid out target water quality values for nutrient concentration and indicator organism counts for these activities. These will be outlined and discussed in detail in the following sections. It is critical that the nutrient concentrations and bacteria counts are compared to these target values as the implications for the STW in terms of effluent quality standard, and the impacts of the users if target values are not achieved may be severe. These impacts will be discussed in further detail under the relevant subsections. In general, nutrient levels in the STW final effluent did not achieve high levels of nutrient removal or disinfection and some have only achieved compliance to the general limits for one of the parameters required by the NWA.

Phosphorus

Out of the 14 STW used in this study two works consistently exceeded the general limit of 10mg/l (Figure A.3). The standard deviations around the mean values for all works were large and Middelburg, Fort Beaufort and Cradock occasionally exceeded the general limits. The standard deviations also show that phosphorus removal efficiency for the Bedford, Middelburg and Kelvin Jones works were highly variable which implies that an environment for consistent phosphorus removal was not adequately maintained. These results show that high levels of phosphorus are regularly released into the environment via effluent of STWs.

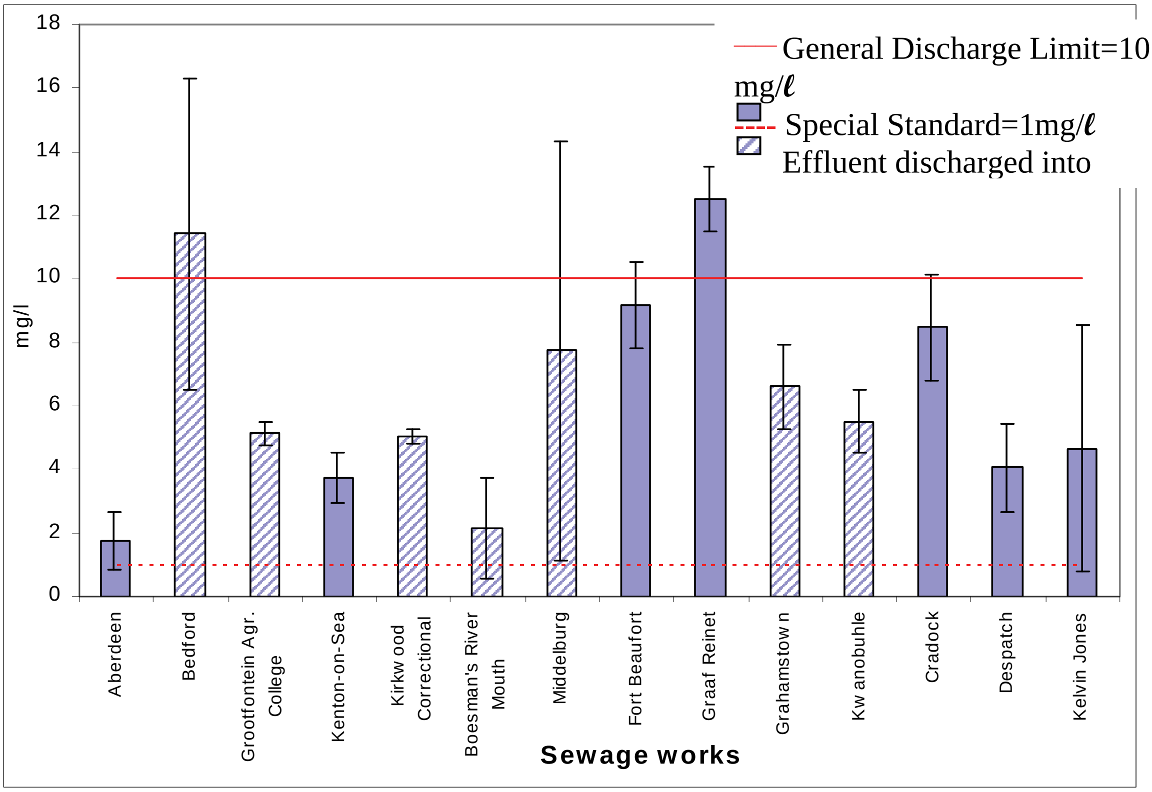


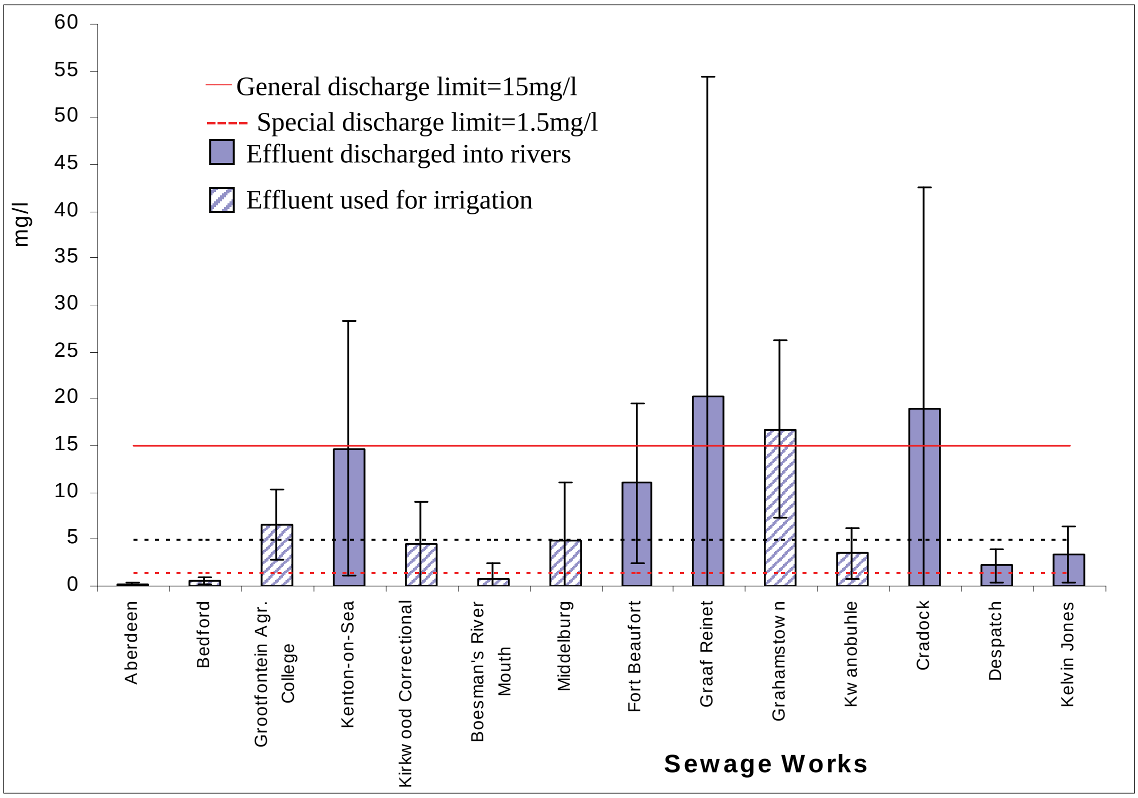
Figure A.11; Phosphorus (soluble) levels in final effluent of 14 sewage treatment works in the Eastern Cape.

DWAF (1996) has not stipulated target values for phosphorus concentrations in effluent used for irrigation or for discharge into a water body used for recreational purposes. Target water quality ranges have been set for phosphorus concentrations in aquatic ecosystems but not for other water uses. Phosphorus is an essential plant nutrient and by stimulation of algal growth, excess levels cause eutrophication of water bodies. It follows that phosphorus concentrations should be of similar concern for crop irrigation as nitrogen with respect to crop and equipment damage. The availability of phosphorus to aquatic biota depends on the pH of the water and oxygen levels and target water quality values have been set accordingly (DWAF, 1996).

<u>Nitrates and Nitrites</u>

Nitrites and nitrates are given as a combined concentration as this was the method used by the STW. The Graaff Reinet, Grahamstown and Cradock works on average exceeded the general limit of 15mg NO_2-NO_3/ℓ of effluent (Figure A.4). Kenton-on-Sea and Fort Beaufort occasionally exceeded the general limits as shown by the standard deviations. Again standard deviations show the high degree of variability in removal efficiencies of nitrate and nitrite for all works with levels occasionally exceeding 28mg NO_2-NO_3/l. Such high levels of nitrogen species are detrimental to the natural ecosystems of the receiving water bodies as together with high phosphorus concentrations, it causes eutrophication with all the associated negative effects. The irrigation of crops with highly nitrogenous water can be detrimental. Nitrogenous water can also be detrimental to stock which graze on irrigated pastures and drink the water, to irrigation equipment and most importantly it may have detrimental effects on people who use the water for domestic purposes without further treatment (DWAF, 1996).

DWAF's (1996) Water Quality Guidelines set target values at a concentration of ≤5mg for total organic nitrogen content per litre for effluent used in irrigation but does not distinguish between nitrate, nitrite and ammonia concentrations. At concentrations higher than ≤5 mg/ℓ damage to crops and contamination of ground water is likely (DWAF, 1996). Damage to irrigation equipment may occur at concentrations as low as 0.5mg organic-N/ℓ which implies that even when using NO_2-NO_3 concentrations only, all effluent used for irrigation from these STW has been potentially causing damage to irrigation equipment. Figure A4 shows that of the STW which use effluent for irrigation, the Grootfontein Agricultural College and Grahamstown Works on average exceed 5 mg/ℓ in nitrate and nitrite concentration only, implying damage to crops may have been caused, while the Middelburg works releases an average concentration of 5mg NO_2-NO_3/ℓ.



FigureA.12: Combined nitrate and nitrite concentrations in final effluent from 14 sewage treatment works in the Eastern Cape.

Ammonia

The most reliable data obtained was for ammonia concentrations in the final effluent as it was tested regularly (monthly) for all sewage treatment plants. This, however only serves to reveal the severity of the problem. Levels of ammonia in the effluent of all works exceeded the general limit on one or more occasions (Figure A5). Only three works had an average ammonia release of less than or equal to the general limit.

The release of high concentrations of ammonia from STW into rivers, estuaries and the marine environment has potentially severe impacts on aquatic life and particularly on fish. Fish are highly sensitive to ammonia and even low concentrations can prove lethal. High ammonia release is therefore not only detrimental to the aquatic ecology of the receiving water bodies but also potentially to the local economy as subsistence and recreational fishing may be impacted.

The Middelburg and Graaff Reinet STW are shown to have released effluent with high levels of ammonia and, together with the Bedford and Grootfontein works, show a high degree of deviation about the mean. This variation indicates highly variable removal efficiencies. Of those works which used effluent for irrigation purposes, only two had mean values below the general limit but does not indicate compliance with target values as total organic nitrogen must be considered.

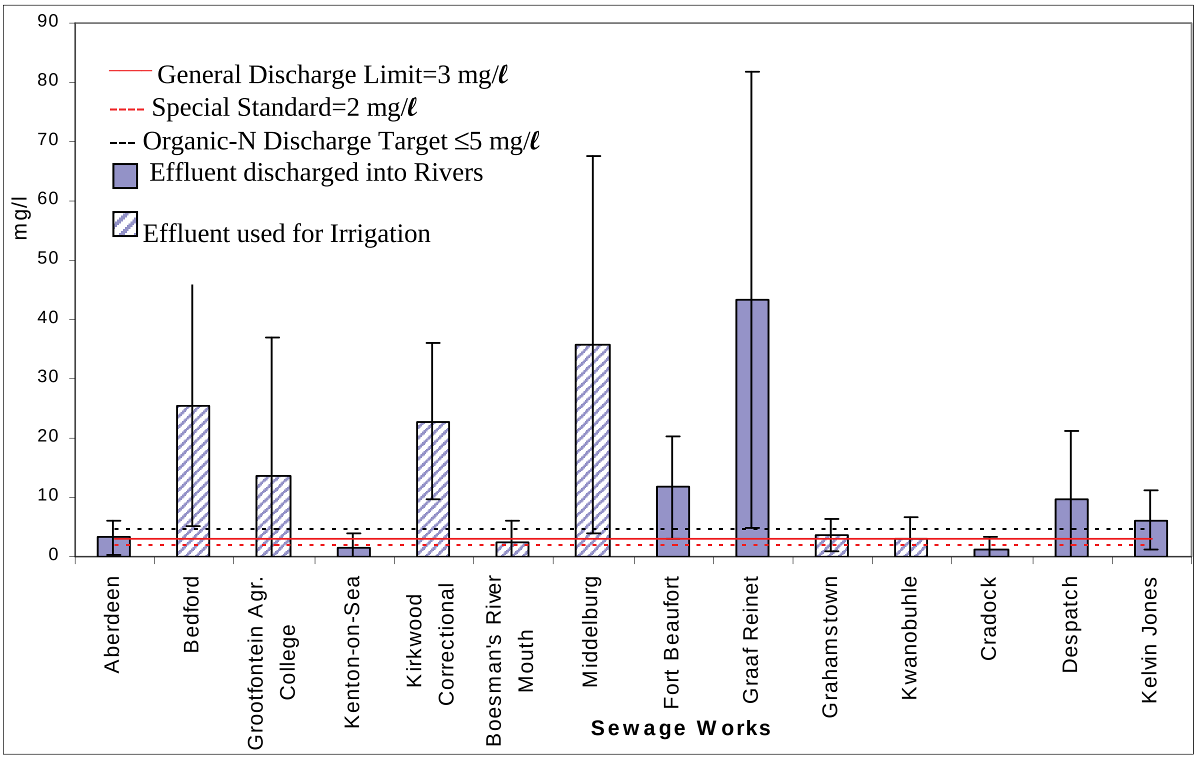


Figure A.13: Ammonia Concentrations in final effluent in 14 Eastern Cape sewage treatment works.

High efficiency in the removal of nitrogen and nitrogen compounds from wastewater is difficult to achieve (Nameche *et al*, 1999) but has, in general, raised little concern as the presence of nitrogen in irrigation water is seen as beneficial as it is a plant macronutrient (DWAF, 1996). However, high concentrations do have negative environmental and economic effects such as those mentioned previously as well as excessive vegetative growth, delayed crop maturity and poor crop quality (DWAF, 1996). Crops vary interspecifically and intraspecifically in sensitivity to nitrogen and nitrogen demand at different stages of growth. Irrigation with highly nitrogenous wastewater can cause low yield, poor quality crops (DWAF, 1996). Irrigation of pastures used for grazing with highly nitrogenous wastewater is also hazardous to animals, particularly ruminants as nitrate is reduced to nitrite in the anaerobic environment of the rumen (DWAF, 1996). This is highly toxic to the animal and causes nitrite poisoning or methaemoglobinaemia (DWAF, 1996) which also affects humans, particularly infants (Horan, 1990; Morrison *et al*, 2001; Clarke, 2002; Dekker, 2002). Nitrogen in irrigation water also stimulates the growth of algae which can clog valves, sprinklers and filtering systems of irrigation equipment. Thus algal production which cannot be harvested may incur high maintenance costs for equipment, irrigation canals and storage dams (DWAF, 1996). Nitrogen concentrations higher than the target value of ≤5 mg/ℓ, also greatly increases the likelihood of groundwater contamination especially if the wastewater is high in nitrate and nitrite.

From the results, it is clear that most of the STWs need to increase their nitrogen removal efficiency if effluent is to be used for irrigation without impacting on the crops irrigated, the ground water, irrigation equipment and livestock. No target values have been set for minimum nitrogen concentrations for release into recreational waters.

Many STWs release effluent into the aquatic environment, which under the NWA, is defined as a water user and target values have been set by DWAF (1996) for minimum impact of water quality on aquatic ecosystems. Nitrogen concentrations of below 0.5 mg/ℓ are considered to be low enough to reduce the likelihood of eutrophic conditions (DWAF, 1996). Ammonia as a component of inorganic nitrogen has been dealt with separately in the guidelines, as concentrations are temperature and pH dependent. The target water quality range for un-ionised ammonia is given at ≤ 7 µg/ℓ. 15 µg/ℓ is given as the 'Chronic Effect Value' and 100 µg/ℓ is given as the 'Acute Effect Value' (DWAF, 1996). Dilution of wastewater alone cannot achieve the target water quality range for nitrogen as evidenced by the presence of eutrophic rivers and dams in the country and in the province (Ashton *et al*, 1996; National State of the Environment Report, 1999). Low flow due to water extraction and droughts also contributes to eutrophication by decreasing the river's assimilation capacity. In this light, it can be suggested that adequate removal of nutrients during times of low flow is particularly important in maintaining adequate water quality for downstream users. A number of STWs rely on biologically-mediated processes for the removal of nitrogenous compounds from wastewater and in trickle filter systems, nitrifying bacteria must compete with heterotrophic bacteria for the available oxygen (Horan, 1990). High COD concentrations in the effluent of many of the provincial STWs suggest that the initial organic loading rates are very high, and would therefore inhibit nitrification. This would then offer an explanation for the poor removal of ammonia at many of the STWs. Ponding systems are frequently employed as the only treatment technology at many of the STWs in the province and as the performance of waste stabilization ponds is a function of retention time, exceeding the specified volumetric loading rates would decrease the nutrient and pathogen removal efficiency of these systems (Horan, 1990).

<u>Disinfection</u>

Despite the importance of bacteriological status of effluent in terms of health impacts, bacteriological monitoring was carried out less frequently than the monitoring of the above nutrients. In many cases only two or three samples were reported for each works since the beginning of 2001.

<u>Faecal Coliforms</u>

Only 8 of the 14 treatment plants achieved an average of the general standard (1000 CFU/100 mℓ) in their final effluent (Figure A.6.) and of these a further three works exceeded the general standard intermittently. Sampling was carried out infrequently and in three cases only two samples were taken and in four cases only 5 samples were taken in a 14-month period. The Fort Beaufort works was the only plant that sampled effluent for faecal coliforms regularly (once and sometimes twice a month) but counts remained variable with a high average of approximately 3000 CFU/100ml. Kirkwood

Correctional Services, together with Grootfontein and Middelburg, showed counts of over 106 CFU/100ml.

The implications of these high figures with the high standard deviations are that treatment was not effective and that the wastewater was not sufficiently disinfected for release into the environment. Faecal coliform levels, as already highlighted, are used to indicate the degree of disinfection and therefore the possible presence of pathogens. The release of such high concentrations as shown in the graph (Figure A.6.), poses a severe threat to human health. Waterborne diseases, such as dysentery and cholera, are of particular threat to the health of poorer and rural communities who rely on ‘raw’ or untreated water for all their water needs. This health threat is in turn detrimental to the economy of the entire province in terms of loss of productivity and medical expenses among other things. It is for these reasons that most S.T.W. are required to chlorinate final effluent before releasing treated wastewater into waterbodies. It is unclear whether monitoring of faecal coliforms was done before or after chlorination.

There are different monitoring requirements for the different size categories of wastewater treatment plants. However, even STW receiving less than $100m^3$ are required by the NWA to monitor faecal coliforms on a monthly basis. While works with capacities less than 1000 m^3 (1 M*ℓ*) monitored nitrate/nitrite and phosphate levels, parameters that they are not required to monitor by law, there was a failure to monitor faecal coliforms regularly.

E. coli

Sampling for *E. coli* was done rarely for the 14 STW and in-depth analysis was not possible. The *E. coli* data was patchy to a level which rendered it of little other use than to give a limited insight into the situation of bacteriological monitoring. In five cases the general limit was met. However, this data does not reflect the whole picture as in each case only a single sample was taken for each over the entire sampling period. The treatment plants of the Kirkwood Correctional Services, Fort Beaufort and Kwanobuhle recorded average counts of between 1,000 and 18,000 CFU/m*ℓ*. No data was available for the other 6 STWs.

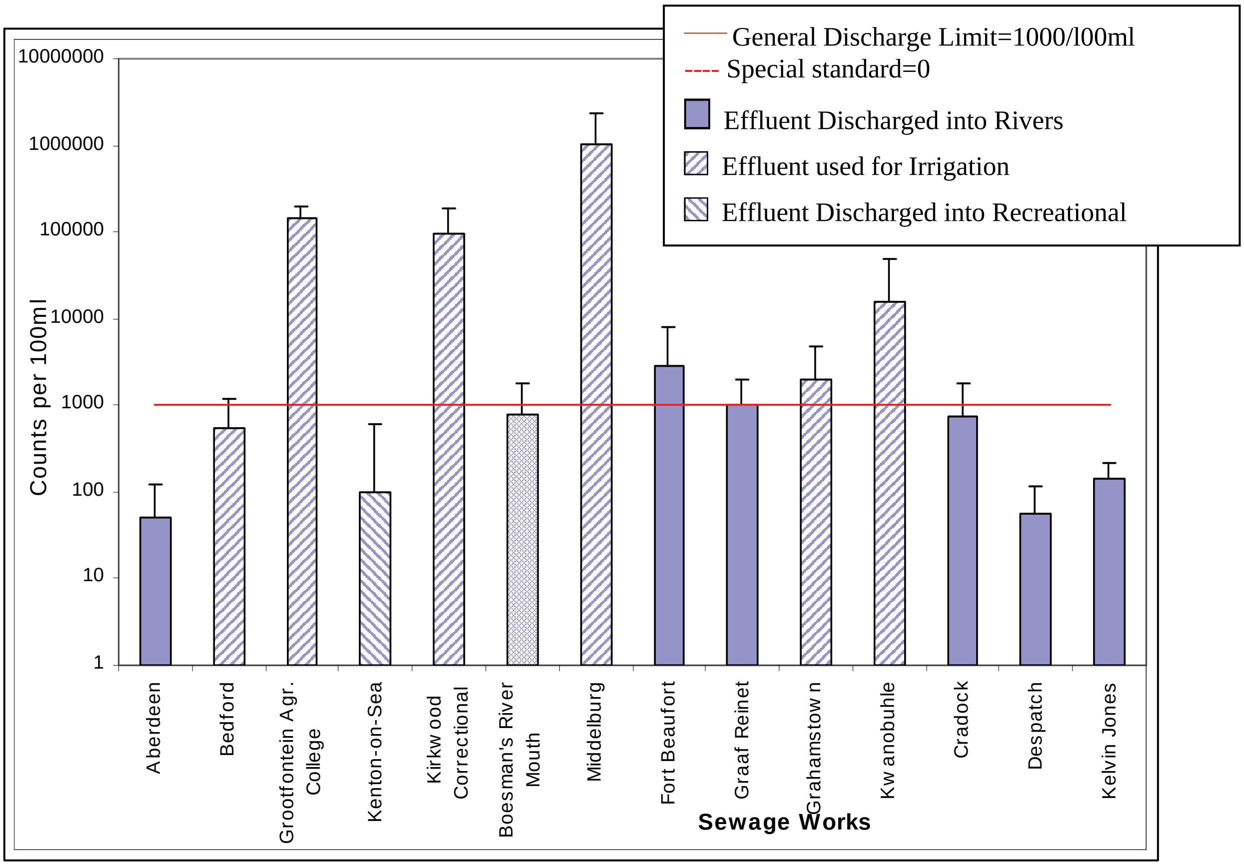


Figure A.14: Faecal coliform counts per 100ml of final effluent in 14 Eastern Cape sewage treatment works.

E. coli levels are often monitored together with faecal coliforms to give an idea of the bacteriological or pathogenic status of effluent and therefore the efficiency of the wastewater treatment system. The target water quality range for water bodies receiving wastewater and used for full contact recreation, e.g. swimming, is between 0 and 150 CFU/100mℓ and between 0 and 130CFU/100mℓ (DWAF, 1996). Intermediate contact recreational use is required to have 0-1000 CFU/100mℓ (DWAF, 1996). Water used for livestock should have a maximum of 200 CFU/100mℓ and water used for irrigation should have less than 1 CFU/100mℓ (DWAF, 1996). Results indicate that effluent from few of the STWs investigated should be used directly for irrigation, livestock watering, or release into recreational waters without substantial dilution.

STWs rely on the natural assimilation capacity of the receiving water bodies and the dilution of the effluent to reduce nitrogen and phosphorus concentrations and faecal coliform counts to more acceptable levels. However, if effluent does not achieve regulation concentrations, it is highly doubtful that the DWAF (1996) target values can be achieved after dilution.

11.4.4 Performance Assessment

A follow-up performance assessment was conducted in 2003 and revealed a similar picture to that outlined by the analysis of the 14 STWs. Out of the 189 works, effluent quality data was available from 97 STWs and compared to the general limit criteria for discharge of wastewater into a non-listed water resource (National Water Act, 1998). As can be seen from Table A.4, of the 97 STWs for which discharge data were available, approximately 56% (54 facilities) discharged the treated effluent to river systems and a further 31% (30 facilities) used the treated effluent for irrigation. The remaining facilities discharged either to the sea or forests. Only 6 of these 97 facilities met the limits for all seven criteria (Table A.4). Again, this is likely to be a conservative estimate as STWs for which even one of the seven criteria was not available were considered as non-compliant. Nevertheless, the results support the 2002 data as well as the findings of Fatoki *et al*. (2003) and suggest that the performance of the STWs in the province could have a considerable negative impact on the quality of water in the receiving bodies and, subsequently, the health of those relying on the rivers for their primary source of water.

Table A.15. A summary of the fate and compliance status of treated effluent from sewage treatment works in the Eastern Cape, South Africa. Data only represents those sewage treatment works for which at least some data were available for the study period.

	Region		
	Port Elizabeth	Umtata	East London
Total STWs	34	32	31
No. discharging to river	20	16	18
No. meeting all 7 criteria for discharge to rivers	0	2	4
No. disposing via irrigation	9	13	8

Considering the low number of STWs meeting all seven of the routinely monitored discharge criteria, it was decided to determine which of the seven criteria were most problematic i.e where the discharge limit for a criterion was not achieved by more than 50% of the STWs. While pH, COD, SS and ammonia (NH_4) data were available for nearly all 97 facilities, this was not the case for NO_2-NO_3 (as nitrogen), phosphorus and faecal coliform data (Figure A.7). As in the previous study only 73 of the 97 STWs (75%) were recorded and, therefore, only 38.6% of the 189 facilities in the province, despite the importance of the latter criteria with respect to the health risk posed to downstream users of the receiving water.

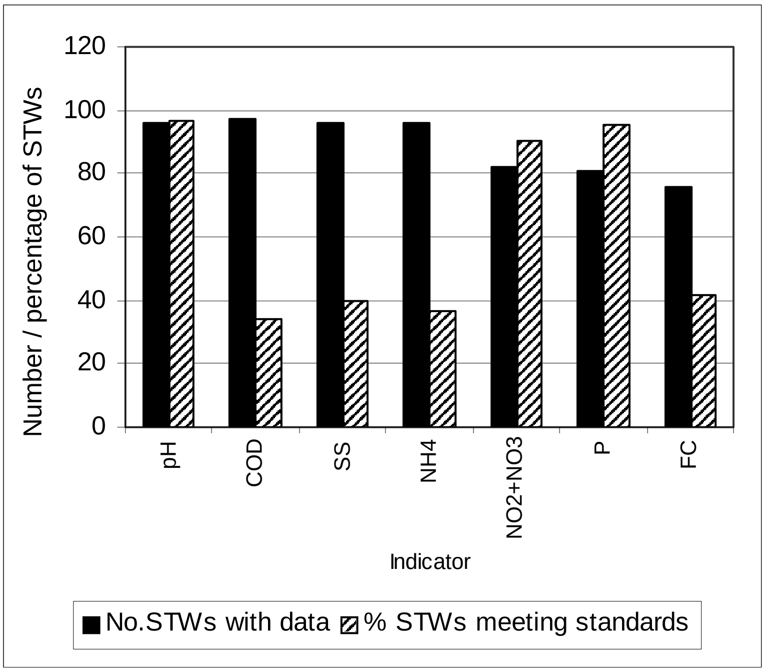


Figure A.15: Performance of sewage treatment works in the Eastern Cape relative to general limits for discharge of wastewater into a water body (NWA, 1998). The percentage sewage treatment works meeting criteria refer only to those facilities for which monitoring data was available. P = phosphorus; FC = faecal coliforms. n = 97

Four of the criteria, namely COD, SS, ammonia and faecal coliforms, were of concern as mean values from the STWs indicated that less than 50% of the 97 facilities were able to regularly meet the required discharge limits (Figure A.7). Again, the mean values were calculated from a very small sample size for some facilities and that in some cases the standard deviations (not shown) were high due to a single very high value. This was particularly true for ammonia and faecal coliform data. Of the STWs for which data was obtained, 9 had mean ammonia concentrations at least an order of magnitude higher than the general limit, with the highest mean of 156mg/L. As discussed above, the temporal variation was often high and one facility recorded an effluent ammonia concentration of 13 mg/ℓ in February 2002 and a concentration of 131mg/L the following month. 18 STWs recorded mean faecal coliform concentrations of greater than 10 times the general limit with the highest mean value of 6.43×10^5 CFU/100 mℓ. As with ammonia concentrations, a number of facilities exhibited variation in effluent quality in terms of faecal coliform counts. For example, the count at one facility was recorded as 43000CFU/100lmℓ for September 2002 and four remaining readings for the study period were below the general discharge limit of 1000CFU100mL.

Correlation analysis (Statistica version 6) was used in an attempt to explain the relatively poor performance of the STWs over the study period. Plant design capacity (plant size), technology type and monitoring frequency were tested for each of the 7 commonly recorded criteria and no significant correlations were found ($p>0.05$). The absence of a correlation with any of the above suggests that plant operation, including hydraulic and organic overloading, are the most likely cause of the poor effluent quality in the region.

Ground Truthing

Visits to various sewage works in the Eastern Cape from 2002 to 2005 revealed that the true situation on the ground confirmed that reflected by the data. A few examples are given which illustrate the findings of the earlier studies. 5 STWs were visited in the Alfred Nzo Municipal District (before re-demarcation of Umzimkhulu into KwaZulu-Natal).

Old Mt Ayliff Oxidation Ponds

Since the commissioning of the new sewage treatment plant at the beginning of 2005, the old oxidation ponds have not received sewage. They do still contain some wastewater which could still pose some health threats (Figure A.8). No rehabilitation of the old ponds has taken place and there is no fencing around the area. In addition a new residential area now extends to less than 50m from the old ponds. There are major concerns caused by the lack of closure of these ponds especially as they pose a health risk to children and stock as they are being used for stock watering. They also pose a threat of disease if these ponds are used for recreational purposes or as a water source by the surrounding communities. The proximity to residences and the steep-sided design mean the ponds also pose the threat of drowning to the surrounding community

Figure A.16: Old Mt Ayliff Oxidation Ponds

Mount Ayliff Sewage Treatment Works (activated sludge)

The new Mt Ayliff sewage treatment works is an activated sludge treatment works (Figure A.9). This site was run by 3 employees. At the time of the site visit, the works employees were experiencing problems with sludge settling and therefore sludge wash-out. No sludge has been generated in the system due to this problem. Employees expressed their lack of access to knowledge support and a strong desire for more training on this aspect of the new works. This demonstrates a lack of operator skills necessary to run activated sludge plants, especially in remote areas. Due to lack of correct operation, sludge was being washed out into the receiving environment thus causing high COD, eutrophication and bacteriological contamination. This STW poses a severe threat to the health of the environment and the community despite its brand new, fully functional infrastructure.

Figure A.17: The new activated sludge system in Mt Ayliff**.**

Umzimkhulu Oxidation Ponds

These ponds were filling with sludge which compromises the efficiency of the anaerobic pond. Upgrading and excavation of sludges would be required to allow it to function at design capacity and for suitable sewage treatment to meet discharge standards.

Umzimkhulu Hospital Oxidation Ponds

The Umzimkhulu Hospital ponds were in good condition with a flow rate far less than the design capacity. The location of these ponds are, however, a concern as they are located upstream of the drinking water abstraction point for the town of Umzimkhulu. On a visit in 2002 the effluent was observed to be running directly into the Umzimkhulu River. This situation had subsequently been altered to run into a soak-away trench in 2005. The effluent volumes were such that evaporation and infiltration was sufficient to prevent ponding of the effluent. This situation still poses a serious threat to the community of Umzimkhulu should the water treatment system fail to reach required standards of disinfection.

Clydesdale Oxidation Ponds

Although informed by the works manager that these were functioning, it was clear on visiting that these have not been functioning for some time (Figure A.10). A severe leak was observed in the outfall pipe and wastewater was flowing alongside the nearby stream for >100 m before flowing into it. A large wetland had developed as a result of this situation. The oxidation ponds were empty and the inlet of the works was blocked. A thorough investigation and repair of the outfall works was essential. A ‘honey sucker’ was said to be used to empty septic and conservancy tanks as well as pit latrines, however, there was no evidence on the site that any vehicle has been there in some time.

Figure A.18: Clydesdale Oxidation Ponds, showing empty ponds and sewage contaminating a local stream.

Rietvlei Hospital Sewage Treatment Works (activated sludge)

The Rietvlei Hospital treats all hospital wastewater at an activated sludge package plant (Figure A.11). The hospital employs a full-time operator for the incineration of hospital waste, water treatment and the operation of the sewage treatment plant. Although the plant was generally well run, with sludge utilised by the surrounding communities for soil amendment purposes. The operator was unaware of the health threat that sludge might pose to the community utilising it as a soil conditioner. This indicates gaps in the training of the operator. The effluent from the treatment system ran into two maturation dams and then onto a field adjacent to a stream where a small wetland had developed.

Figure A.19: Package plant activated sludge system at Rietvlei with two piles of sludge visible on the right of the sludge drying beds in the foreground.

Mt Frere Sewage Treatment Works (activated sludge)

A large new activated sludge treatment works has been built in Mt. Frere (Figure A.12). Despite the large size, this site was run by 2 employees. Due to the lack of employment in the area, there were many volunteers working at the site in the hope of being employed. No sludge had been generated as yet due to recent commissioning. Again, the plan was to allow communities to remove sludge for soil amendment.

Figure A.20: The sludge drying beds at Mt. Frere activated sludge works (left) with the inlet works (right).

11.5 CONCLUSIONS

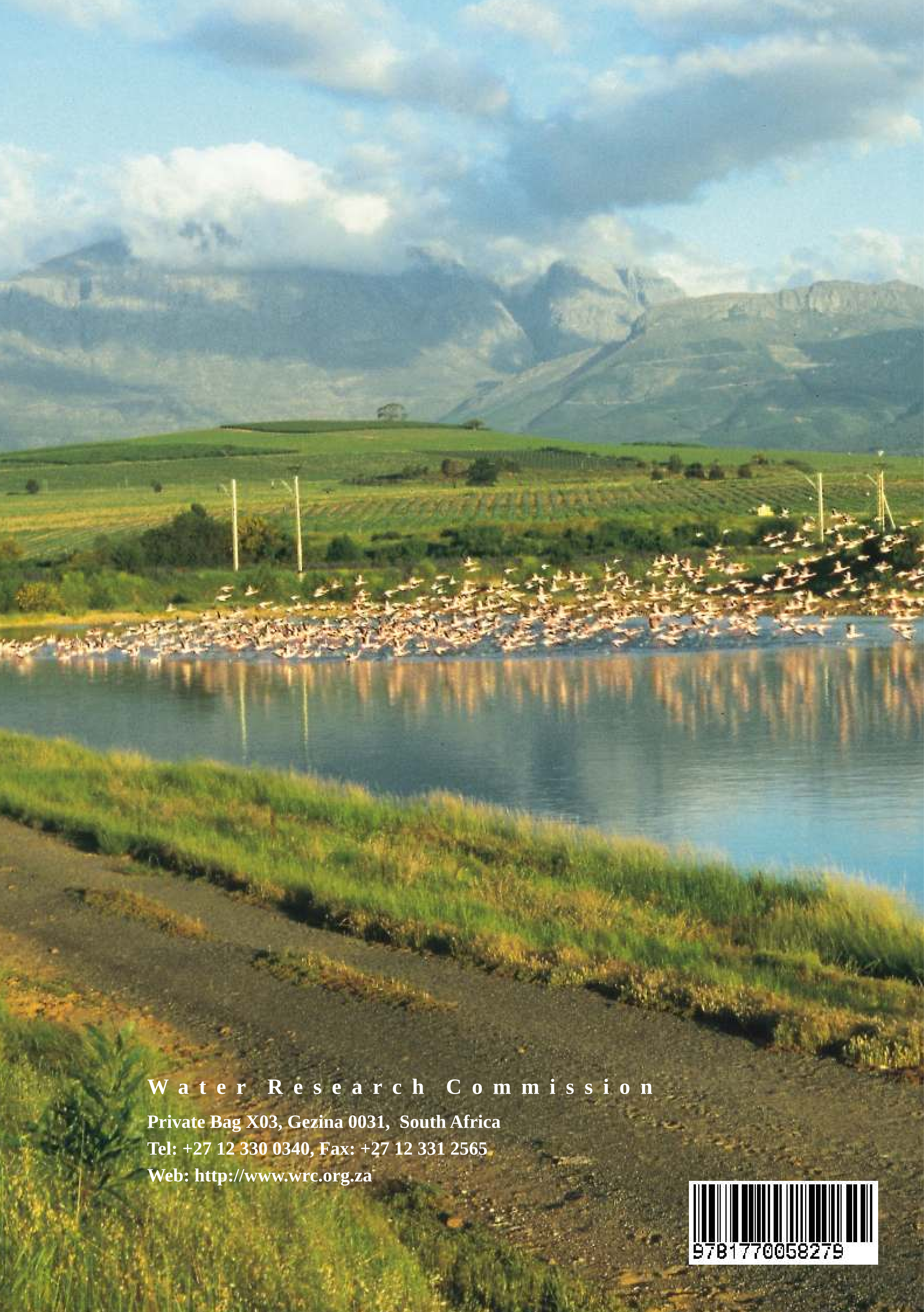
From the various studies and site visits, the following conclusions can be drawn:

1. 74% of wastewater treatment plants in the Eastern Cape were designed with a capacity of less than 1 Mℓ/day;
2. No clear correlation between capacity and efficiency or between the efficiencies of treatment technologies relative to the capacity of works could be established;
3. The nutrient status of the effluent being discharged from Eastern Cape STWs is generally poor and not in compliance with the general limits. This varied within individual works and between works. 14% of surveyed works consistently achieved the DWAF phosphorous discharge standard of 10 mg.ℓ^{-1}. 64% consistently achieved the nitrate-nitrite discharge standard of 15 mg.ℓ^{-1}. 21% of surveyed works achieved average ammonia discharge levels of less than the 3mg.l^{-1} with no works consistently achieving this standard. Ammonium concentration poses the largest compliance problem for the majority works, although lack of disinfection poses the largest health risk to humans;
4. Disinfection status of the discharged effluent was not established with any degree of certainty due to the low reliability of the data. Monitoring frequency for faecal coliforms in surveyed works was not carried out monthly as required by law. 43% of plants monitored faecal coliforms at less than 5 times in a 14 month period and only one of the surveyed works had monthly faecal coliform data which were nevertheless extremely high and exceeded the required levels of 1000CFU/100 mℓ.

Faecal coliform counts obtained revealed extremely high levels posing a serious threat to downstream community and ecosystem health;

5. From the nutrient status and disinfection levels of monitored effluent, it can be concluded that effluent quality and therefore treatment efficiency is not consistent and generally inadequate at sewage treatment plants investigated in the Eastern Cape;
6. Both old and new STWs pose a threat to the health of the environment and the surrounding communities mostly due to lack of operator skills, support, knowledge as well as lack of awareness of the threats STWs can pose.

Results from the current study showed that a large proportion of the STWs in the Eastern Cape Province of South Africa were unable to regularly produce an effluent that met the general discharge limits as specified in the South African National Water Act (1998). As such they are likely to pose a significant threat to the health of local ecosystems and those communities who rely on the receiving waters for drinking, cooking, washing and recreation.



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