ANAEROBIC BIOCONVERSION OF THE ORGANIC FRACTION FROM THE FRUIT PROCESSING INDUSTRY

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DECLARATION

I, the undersigned, hereby declare that the work contained in this thesis is my own original work and that it has not previously, in its entirety or in part, been submitted at any other university for a degree.

Wilmaré Griessel

CONTENTS

Language and style used in this thesis are in accordance with the requirements of the *International Journal of Food Science and Technology.* This thesis represents a compilation of manuscripts where each chapter is an individual entity and some repetition between chapters has, therefore, been unavoidable.

ABSTRACT

South Africa is a developing country that relies heavily on its agricultural sector for economical welfare especially in the Western Cape Province. However, development gives rise to new technologies, new products, economical stability and unfortunately also to the production of larger volumes of liquid and solid waste.

Anaerobic composting is becoming a very attractive treatment option for solid waste disposal because of its unique operational advantages and two value-added by-products, compost and biogas. Over the last decade progress has been made in anaerobic digestion of solid wastes, but no literature could be found on the anaerobic composting of apple and peach pomace.

The main objective of this study was to develop a method to anaerobically compost apple and peach pomace. In the first phase important operational parameters were identified and a method was developed to optimise the parameters. In the second phase of the study, the scaling-up and optimisation of the process were the major objectives.

During the first phase of this research 2 L modified glass containers were used as composting units. The most important operational parameters (leachate pH, inoculum source and size, and initial moisture levels) were identified. Anaerobic compost from previous tests, brewery granules and anaerobic sludge were also used as inocula and evaluated for the best source of microbes. After optimising all the identified parameters, good results were obtained, which included higher biogas production, good volume reductions, less bad aromas and a compost product with a neutral pH.

After developing the 2 L laboratory-scale method to compost the apple pomace anaerobically, the next step was to ascertain if the method would work if larger volumes of solid fruit waste were composted. A special 20 L composting unit made of PVC was designed to suit the operational requirements of the anaerobic composting process. It was also decided to mix apple pomace and peach pulp together and to use this solid waste source as part of the composting substrate.

Different inocula, including cattle manure, anaerobic sludge, brewery granules and anaerobic compost produced in the previous tests, were used.

Although good results were obtained with the anaerobic compost and cattle manure as inoculum, the aim was also to decrease the composting period by shortening the pH stabilisation period. To achieve this, it was decided to add $NaHCO_3$ to the substrate to be composted to facilitate a faster pH stabilisation. The composting period was subsequently shortened to 25 days with satisfactory results, which included a volume reduction, biogas production and faster pH stabilisation.

An upflow anaerobic sludge blanket (UASB) bioreactor was also used to assist the composting process by facilitating the removal of the VFA's present in the composting leachate. This proved to be a valuable addition to the composting process as the UASB bioreactor also provided the composting units with a 'moisturising liquid', which was 'enriched' with a consortium of active anaerobic bacteria when the effluent from the bioreactor was re-added to the composting units.

With all the operational parameters in place, good results were obtained and these included a volume reduction of 60% (m/m), a good biogas production, a composting period of only 25 days, a compost that was free of bad aromas, a final compost pH of > 6.5, final leachate COD values of less than 3 000 $mg.l^{-1}$, and a final leachate VFA's concentration of between 0 and 250 $mg.l^{-1}$.

If in future research further scaling-up is to be considered, it is recommended that the composting unit be coupled directly to the UASB bioreactor, thus making the process continuous and more practical to operate. If the operational period of the anaerobic composting set-up could be further shortened and the inoculum adapted so that the process could be used for the treatment of other difficult types of solid wastes, it would probably be advantageous for the fruit processing industry to use this method as an environmental control technology.

UITTREKSEL

Suid-Afrika is 'n ontwikkelende land wat baie afhanklik is van die sukses van die landbousektor vir ekonomiese welstand, veral in die Wes Kaap Provinsie. Ontwikkeling gaan gepaard met nuwe tegnologie, nuwe produkte, ekonomiese stabiliteit en daarmee saam gaan die produksie van groter volumes vloiebare en soliede afvalprodukte.

Anaërobiese kompostering is tans besig om opgang te maak as 'n doeltreffende behandelingstegnologie vir vaste afvalstowwe. Tydens die laaste dekade is baie vooruitgang gemaak in die veld van anaërobiese vertering asook kompostering van afvalmateriaal met 'n hoë vaste stof inhoud. Anaërobiese kompostering van appel- en perskepulp, afkomstig van die versappingsindustrie, het tot dusver min aandag geniet.

Die hoofdoel van hierdie navorsing was om 'n anaërobiese komposterings metode te ontwikkel vir die behher van vrugte afval om sodoende die basis neer te lê vir 'n nuwe tegnologie wat baie voordele (biogas en kompos) inhou. In die eerste fase is die belangrikste operationele parameters geïdentifiseer om sodoende beter beheer oor die anaërobiese proses uit te oefen. In die tweede fase is die anaërobiese proses wat gedurende die eerste fase ontwikkel is, opgeskaal om optimum resultate te verkry.

Gedurende die eerste fase van hierdie verhandeling was 2 L gemodifiseerde glas houers gebruik as komposteringseenhede. Die belangrikste operasionele parameters (pH beheer, inokulasie grootte, vloeistofvlakke en hoeveelheid vog asook vlugtige vetsuur produksie en verwydering) vir die beheer van die anaërobiese komposteringsproses was geïdentifiseer en gebruik as uitgangspunt om 'n anaërobiese komposteringsmetode te ontwikkel. Anaërobiese slyk, brouery granules en anaërobiese kompos van vorige eksperimente was as inokula gebruik. Gedurende hierdie studies was goeie resultate verkry en het 'n hoë biogas produksie, goeie volume reduksies, vermindering van slegte aromas en kompos met 'n neutrale pH ingesluit. .

Nadat hierdie goeie resultate met die 2 L laboratorium-skaal metode verkry was, was groter volumes vaste vrugte afval gebruik om te bepaal of die dieselfde metode toegepas kan word op 'n groter skaal. Spesiale 20 L komposteringseenhede was ontwerp om aan die operationele vereistes van 'n

anaërobiese proses te voldoen. Dit was ook besluit om appel pulp met perske pulp te meng en te gebruik as deel van die komposteringssubstraat.

Verskeie inokula was weereens gebruik en het die volgende ingesluit: vars beesmis, anaërobiese slyk, brouery granules en anaërobiese kompos van vorige eksperimente. Hoewel baie goeie resultate met vars beesmis en anaërobiese kompos as inokula verkry was, was 'n volgende doel gewees om die kompoterings tydperk te verkort deur die pH vinniger te stabiliseer. Daar was besluit om $NaHCO_3$ by die komposteringssubstraat te voeg en so 'n vinniger pH stabilisasie te fasiliteer.

'n UASB ('upflow anaerobic sludge blanket') bioreaktor was ook gebruik om die komposteringsproses aan te help deur die vlugtige vetsure wat in die kompostloog teenwoordig was, te verwyder. Die insluiting van die bioreaktor in die anaërobiese komposteringsproses het bygedra tot die sukses van die proses deurdat die uitvloeisel as 'n vogmiddel vir die komposteringseenhede gebruik was en 'n konsortium van aktiewe anaërobiese bakterieë bevat het.

Nadat al die operationele parameters in plek was, was goeie resultate bereik en het die volgende ingesluit: 'n volume reduksie van 60% (m/m), goeie biogas produksie, 'n komposteringstyd van 25 dae, 'n kompos wat vry was van slegste aromas, 'n finale kompos pH van >6.5, finale loog CSB van <3 000 $mg.l^{-1}$ an 'n finale vetsuur konsentrasie van tussen 0 en 250 $mg.l^{-1}$.

Indien verdere navorsing onderneem word, word dit aanbeveel dat die UASB bioreaktor direk aan die komposteringseenheid gekoppel word om sodoende die proses meer aaneenlopend en die proses prakties makliker uitvoerbaar te maak. Indien die operationele tydperk nog korter gemaak kan word en die inokulum aanpasbaar kan wees om moeilik verteerbare afvalprodukte te akkomodeer, sal hierdie tegnologie baie voordelig wees as 'n metode om omgewingsbesoedeling te beheer

dedicated to my parents and Johan

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CHAPTER 1

INTRODUCTION

Large volumes of fruit and vegetable solid wastes are produced in fruit packing plants, canneries and juice manufacturing factories. The disposal of these food wastes has become a major concern, mainly because of the high moisture content (75 – 80% m/m). As a result, traditional disposal methods are usually not applicable and may even be responsible for further serious environmental pollution problems like groundwater pollution, attraction of vermin, air pollution and spreading of diseases to name a few (Kim *et al.*, 2000). Many food-processing industries are faced with the problem of managing solid wastes, which can constitute up to 30% (m/m) of incoming raw materials. Dealing with the solid waste is becoming an urgent matter for many of these industries, as landfill sites are being minimized or even closed as operators restrict the quantity of waste that can be brought into landfill sites. Furthermore newer regulations have nullified some of the previously used disposal practices (Schaub & Leonard, 1996).

The fruit processing industry is a large division of the processing industry and according to the South African Canning Fruit Producers' Association, 241 084 tons of fruit (apricots, peaches and pears) were processed during the 1999/2000 season. The fruit is generally used to produce juice, jam and juice concentrates (Victor, 2000).

A typical example is Appletizer which is a large South African fruit juice company which is situated in Grabouw and is well known for the production of apple juice as part of the processing of between 55 000 and 100 000 tons of apple and pears each year (Du Randt, 2000). After the juice is extracted, the producer ends up with a pomace, which constitutes up to 10% (m/m) of the apple. The producer has no further use for the pomace and has to dispose of it some or other way. Usually the pomace is sold, dried and used as animal feed, but this is not very profitable and the company is waiting for new technology to improve profits (Du Randt, 2000). Anaerobic composting could most definitely be a possible solution.

Another example is Ceres Fruit Processors who processes between 80 000 and 90 000 tons of apples and pears each year to produce juice concentrates.

According to Mr. May (2001), the pomace does not at the moment present a serious problem as it is sold to farmers for about R 10 per ton to use it as animal feed. The greatest problem concerning the factory at the moment is the solid fruit waste in the effluent that is being separated by filters before it reaches the anaerobic treatment facility. This waste cannot be sold to the farmers because of the high pH (9.0 – 10.0). In the past this waste was sent to the local landfill at high cost, but this will not be possible in the near future (May, 2001) as the Ceres Valley has been declared an aquasphere that provides the Western Cape with drinking water. As a result all landfills in the area will have to be closed down within the next two years to minimize the pollution of the groundwater. The only alternative for Ceres Fruit Processors will be to transport the waste to landfills in Wolseley at great cost. Thus, the company is looking for new ways to deal with the solid waste problem as transportation of this waste is becoming more expensive as the cost of fuel increases (Du Toit, 2001). Anaerobic composting could help to solve the problems by reducing the costs of increasing transportation fees to landfills by using the fruit wastes to generated methane and compost on the plantation site.

In the case of the Ceres Municipality, pomace and solid fruit wastes that have been disposed of on the local landfill sites are the cause of major disposal difficulties. According to the Head of the Department of Health at Witsenberg (Du Toit, 2001) this waste is very wet and makes it difficult to compact with other waste, thus creating disposal and health problems at the local landfill sites especially by attracting flies and vermin.

Ashton Canning Co (Pty) Ltd. processes about 60 000 tons of fruit each year. The pomace and pulp fractions that are produced are sold at a very low price that does not provide any regular means of income. However, the factory uses charcoal to generate heat for the factory. According to Van Niekerk (2001), the charcoal is very expensive and the management of the company is looking for a different alternative, which could include the generation of biogas from the anaerobic digestion of the pomace (Van Niekerk, 2001).

Elgin Fruit Juices in Grabouw (Van Zyl, 2001) produces fruit juice throughout the year. Of the 70 000 tons of fruit that is processed, 0.5% ends up spoilt and has to be disposed of. Currently, the company is paying another company to dispose of the spoilt fruit to a landfill site. This is a heavy economical

loss for Elgin Fruit Juices each year, funds that could have been invested in the company itself. Anaerobic composting could be developed to be a modern technology that could benefits fruit processing factories because of the obvious advantages of compost production and biogas generation.

When considering all the above-mentioned disposal problems, it is understandable why juice, jam and concentrate producing factories are looking for an alternative method of dealing with the solid fruit waste. At present, the upflow anaerobic sludge blanket (UASB) technology is providing treatment assistance with leachate disposal to many factories in the fruit processing industry (Van Zyl, 2001). But, the time has come to develop a new form of anaerobic technology to help the fruit processors in South Africa with their solid fruit waste dilemma (Van Zyl, 2001).

South Africa is a developing country that relies heavily on its agricultural sector for economical welfare especially in the Western Cape. However, development gives rise to new technology, new products, economical stability and unfortunately also the production of larger quantities of liquid and solid wastes.

Management of waste is not only a South African, but also a world dilemma. The world is currently facing the problem of global warming and pollution of the environment. What in the past appeared to be excellent waste management methods (landfilling and land irrigation) is today's biggest concern when methane emissions and pollution of groundwater are taken into consideration. Beside the normal solid wastes, many thousands of tons of fruit and vegetables also go to waste each year in packaging plants, canneries and juice producing factories. Disposal of these large quantities of wet, organic solid wastes generated during the fruit and vegetable processing operations creates economic and environmental problems to which no fully satisfactory solutions have as yet been found. At present, drying and thereby generating animal feed, dispose of large quantities of fruit and vegetable solid waste, but this method has its own characteristic problem (Anon, 1999; Lane, 1984).

Four well-known possible treatment strategies are available to dispose or re-utilize solid waste and these include incineration, landfill, recycling and anaerobic composting. Incineration is presented as a clean technology, at least at first sight (Sequi, 1996). Disposal of waste by incineration does allow energy recovery, so that theoretically after initial supply of fuel, a self-sufficient energy

supply internal to the cycle should occur. Looking closer, incineration does reduce the volume of waste substantially, but not always the mass. For instance, when municipal solid waste is incinerated, about one third of the initial weight is transformed into inorganic matter, but this still needs to be disposed of at high rates. The energy recovery on the other hand is very poor (Sequi, 1996).

Landfilling is another technology that appears feasible and wastes are disposed without apparent difficulties in appropriately selected areas (Albaiges *et al.,* 1986). The first obstacle however, is the insufficiency of appropriate land surface. Due to this, landfilling has become extremely expensive. A number of adptions are now required legally to ensure that landfill sites do not leak polluting leachate into the groundwater and this of course adds additional expenses (Albaiges *et al.*, 1986; Anon., 1998).

Recycling is probably the most difficult option to practise, as it requires a high degree of professional competences, making it unpopular to put into operation. Recycling is the technology, which prevents the existence of waste by transforming materials that could become waste into useful materials or even commercial products (Sequi, 1996).

Anaerobic composting is becoming a very attractive treatment method because of its unique advantages. Two by-products, compost and biogas, can be generated during this digestion process. The compost can be reused in the agricultural sector as a soil conditioner, while the produced biogas can be used to generate heat that will lead to savings in the electricity account (Lusk, 1998; Vogtman, 1996).

Although anaerobic technology for the treatment of solid waste is still relatively young, countries such as Germany, Denmark, Switzerland and a few other European countries are showing increasing interest in the technology (De Baere, 2000). At present, anaerobic digestion (AD) of solid waste is mainly implemented: as part of mechanical-biological treatment of unsorted and separately collected municipal waste; for the treatment of biowaste; and as part of co-digestion of sewage sludge, dry manure or industrial waste (Van Lier *et al.,* 2001).

At present, approximately 1 million tons of organic waste are digested and converted to biogas and a stable residual matter per year worldwide. De Baere (2000) identified a total of 53 plants that use AD as a treatment option for solid

waste. Increasing volumes of waste that have been digested are observed in processing plants each year and an increase of 200 kton per year is expected by the end of 2001. Not only does the digesting capacity of each plant increase, but also more and more anaerobic digesting plants are arising each year in Europe. Most of these plants are constructed in Germany, followed by Switzerland, Belgium, the Netherlands and France (De Baere, 2000).

The aim of this study was to develop a laboratory-scale anaerobic composting method for the treatment of apple and peach pomace solid waste from the fruit processing industry. The process will then be optimised by firstly using different inoculums at start-up. After a suitable inoculum has been identified, the anaerobic process will be optimised by removing the produced leachate fraction from the composting units and replacing it with different 'moisturising liquids' (water, UASB bioreactor effluent and a water and UASB bioreactor effluent mixture). The effect of the 'moisturising liquids' will also be evaluated and the most suitable ' moisturising liquid' identified. The addition and influence of sodium bicarbonate will also be evaluated in terms of process efficiency.

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CHAPTER 2

LITERATURE REVIEW

A. BACKGROUND

Waste and pollution is an inevitable part of life and man has tried for ages to keep up with the problem of waste management. Over the last few decades advanced technologies have become necessary for survival, but the irony is that these technologies are also responsible for further pollution.

Waste management is, in principle, bringing order to used goods, but waste is usually of little use or value. By ordering macro- or micro-components (molecules), one can alter the composition in such a way that the negative character is changed (Verstraete, 2000). Bioconversion is the modern term used to describe the biological conversion process where organic matter is, for example, converted to energy in the form of methane and a humus end-product (Kayhanian & Tchobanglous, 1993). The process can benefit food industries economically and mitigates possible waste pollution problems, thereby sustaining industrial development while maintaining environmental quality. Moreover, rural economic development will benefit from the implicit multiplier effect resulting from jobs created by implementing bioconversion systems (Lusk, 1998). A bioconversion management system not only provides pollution prevention but also can convert a waste problem into a new profit centre. Economic evaluations and case studies of operating systems indicate that the natural digestion of food waste is a commercially viable bioconversion technology with considerable potential for providing profitable co-products, including a cost-effective renewable fuel in the case of anaerobic digestion (AD), which can further be used in food production operations (Edelmann *et al.*, 2000).

C. TRADITIONAL TREATMENT OPTIONS

Landfilling

Landfilling of municipal solid waste (MSW) represents the most extended system of solid waste disposal in the world. It represents the ancient method of nature's breakdown of biodegradable waste. The use of landfills to dispose of

solid wastes is rapidly declining in industrialized regions because of poor sustainability and environmental pollution. Landfill sites can be seen as huge aerobic/anaerobic digesters and although it was generally thought that this might solve the waste problem, more and more reasons for not using landfilling are being found (Wallis, 1994).

Methane is emitted during the anaerobic decomposition of organic waste disposed. In addition to methane, landfills can also produce important amounts of carbon dioxide (CO_2) and non-methane volatile organic compounds (VOC's) (Baldasano & Soriano, 2000). Poor management and operation of landfills in the past are becoming a serious problem as leachate produced in landfills is becoming a major environmental pollution hazard. Various studies have indicated that landfills may have a large impact on groundwater pollution (Britz, 1995). Landfilling is sometimes seen as innovative biotechnology, but others regard it as a burden for next generation. Landfills can take over 50 years to stabilize and represent a waste of useful resources with adverse environmental impacts which also includes the release of bad odours, leachate contamination of groundwater and the attraction of vermin (Albaiges *et al.,* 1986).

Aerobic composting

Aerobic composting is a process in which the stabilisation of organic matter occurs in the presence of oxygen and micro-organisms (Lusk, 1998; Kayhanian & Tchobanoglous, 1993). The end-product is a stable, hygienic substance resembling soil and is rich in humus. In the presence of oxygen, micro-organisms decompose the biodegradable organic matter into compost, which contains nutrients and oligo-elements and is used in agriculture as a soil conditioner (Baldasano & Soriano, 2000).

In nature, the aerobic composting process occurs in two temperature ranges: mesophilic and thermophilic. The microbiota in the mesophilic process (20° – $37^{\circ}C$) is diverse and includes bacteria such as *Pseudomonas* and *Proteus.* Fungi that participate include *Mucor, Rhizopus, Aspergillus, Phanaerochaeta* and *Trichoderma* (Miller, 1993). In contrast, the rate of CO_2 and heat production during the thermophilic process (40° – $70^{\circ}C$) is low and little evaporation of water takes place. Bacteria present include *Bacillus, Streptomyces* and *Thermoactinomyces* and fungi such as *Aspergillus fumigatus, Chaetomium* and *Humicola (*Lapara &

Alleman, 1999). Studies have shown that bacteria are better adapted to breaking down the easily decomposable material, whereas fungi are adapted to breaking down the more difficult material like cellulose and lignin (Miller, 1993).

Although this treatment method appears to be an ideal disposal solution, it is not as effective as one would like and offers a lot of drawbacks. The major limitation of aerobically composted waste from the fruit and vegetable processing industry is the high moisture content that leads to the formation of offensive odours, which subsequently attracts flies and vermin (Schaub & Leonard, 1996). Composting of wastes high in moisture requires considerable amounts of structuring material and its high biodegradability results in a final compost yield that is very poor (Pavan *et al.,* 2000). For mesophilic composting processes, a further problem is experienced with pathogens and weed seeds that are still active after the composting process is finished. The extended composting time period is also an economical limiting factor. Unlike anaerobic digestion, there is no recovery of energy and the process tends to be expensive due to the energy costs associated with continued aeration (Bernard & Gray, 2000).

Incineration

Incineration is the combustion of solid waste to reduce the volume and generally takes place at temperatures between 200° and 300°C and at pressures between 25 and 40 bar (Alexiou & Osada, 2000). Incineration can only be used for residues containing less than 50% water otherwise oil or gas must be added to fuel the combustion process which directly influence the economical efficiency of the process. This method of administrating wastes is effective but not popular as it is costly and can result in the production of CO_2, carbon monoxide (CO), nitrogen oxide compounds (NO_x) and non-methane VOC's, which are difficult to dispose of (Baldasano & Soriano, 2000). The non-gaseous products include fly ash and unburned solids that can make up 30% of the mass of the initial waste. Despite some advantages, a large investment is required, the maintenance and operating costs are high, air pollution occurs, greenhouse gasses are produced, mutagenic chemicals and pollutants are emitted that can lead to acid rain. The efficiency of incineration is very limited as not many types of waste are suitable and may generate toxic gaseous products in conjunction with unburned particles.

Depending on the type of waste, a certain percentage is always not incinerated and has to be disposed of in some or other manner (Anon., 1992; Anon., 1997).

Animal feed

Fruit pomace can also be used as animal feed and can either be fed as a fresh product, ensiled or in a dried form. Two problems are generally encountered when using fruit pomace (especially apple pomace) as a feed ration (Anon., 1999). These include the high concentrations of pesticide compounds found in the pomace, which can make it unacceptable as part of dairy, sheep and cattle rations. The second difficulty is the presence of urea and other non-protein nitrogen compounds in especially apple pomace that may lead to abortions and/or abnormalities in animal offspring (Anon., 1997).

Anaerobic composting

Anaerobic composting (AC) (bioconversion or digestion) represents a new cost-effective strategy for the management of solid fruit and vegetable wastes. Two valuable products are produced with this technology: biogas and a potential fertilizer or compost (Earle *et al.,* 1991; Lomas *et al.,* 2000). Bioconversion presents an ideal solution for the management of solid fruit waste like apple pomace as other traditional treatment methods present shortcomings. In the following section, this treatment method will be discussed in more detail as an option to manage solid wastes produced by the fruit and vegetable processing industry.

D. ANAEROBIC COMPOSTING – A SOLUTION FOR THE FUTURE

Conversion process

Anaerobic composting (AC) is the microbial stabilisation of organic wastes and occurs in the absence of oxygen. The overall AC process occurs through the symbiotic action of a complex microbial consortium with specialized ecological roles (Iannotti *et al.*, 1986). In essence, the process involves the degradation of complex organic molecules (lipids, protein, carbohydrates, etc.) by common food bacteria to volatile fatty acids, carbon dioxide, hydrogen, ammonia and sulphide (hydrolytical and fermentation step). These metabolites are then fermented into

acetate, carbon dioxide and hydrogen. Hydrogen (H_2) and carbon dioxide can then be converted to acetate (acetogenic step). Finally, methane is produced from acetic acid, (H_2) and CO_2 (methanogenic step) (Bryant, 1979; Fang, 2000; Kirsch & Sykes, 1971; Wolfe & Higgins, 1979). The methanogens are seen as the key organisms in the anaerobic process with regard to waste stabilization and will be discussed in more detail (Song *et al.,* 1992). In particular the methanogens have the slowest growth rate and are the most sensitive to environmental changes (Price, 1985).

The anaerobic digestion process is much more complex than a simple 'food-chain' as simply described in the above four steps, as it involves co-metabolism, fermentation interactions and cross feeding of nutrients. Bacteria like sulphate-reducing bacteria are also present and are responsible for the reduction of sulphates and other sulphur compounds to hydrogen sulphide (Lusk, 1998).

Anaerobic composting - process microbiology

Anaerobic bacteria are mostly part of the most ancient line of decent, the archaebacteria, which are only distantly related to other living organisms, including most bacterial species (Scoberth, 1980). The methanogenic bacterial group was discovered in 1868 by Bechamp, a student of Louis Pasteur, as an "organism" that was responsible for methane (CH_4) production from ethanol (Zehnder *et al.,* 1981). Since then, it has been shown that the production of CH_4 is the result of several microbial groups, occurring in several phases. The relationships between the microbes of each phase can be defined as symbiotic, metabolic or even antagonistic, depending on the environmental conditions and substrate composition and concentration (Haulser, 1969). At present, the digestion of organic matter is known to follow the simplified pathway presented in Fig. 1. Within this pathway, the fermentation end-products of one group serve as the metabolites needed for growth for the next group.

Acidogens

Extracellular enzymes, especially the hydrolases, initiate the anaerobic breakdown of the complex substances and are produced by the hydrolytic bacteria. Hydrolases are depended on the type of reaction catalysed and can be esterase, glycosidases or peptidases (Gander *et al.,* 1993). After breakdown is

initiated, the acidogens proliferate on the produced polymer fragments (Iannotti *et al.*, 1986). Polymers like polysaccharides, lipids and proteins are depolymerised to soluble monomers (volatile fatty acids, alcohol, hydrogen and carbon dioxide) that can be readily assimilated into microbial cells and metabolised (Forday & Greenfield, 1983). The principal volatile fatty acids include acetic, propionic and butyric with small quantities of valeric acid.

During acidification the chemical oxygen demand (COD) reduction is minimal. When large amounts of H_2 and CO_2 are present, some COD reduction may occur, but this reduction is seldom higher than 10% (Noike *et al.*, 1985). Usually hydrolysis is the slowest step in biomethanogenesis and considered to be the rate-limiting step in the overall anaerobic digestion process (Noike *et al.*, 1985). In addition, the efficiency of the hydrolysis step contributes to the ultimate methane yield.

Bacterial strains isolated from swine manure and other anaerobic digesters were predominantly Gram-positive anaerobes and included *Peptostreptococcus, Bacteroides, Lactobacillus, Peptococcus, Clostridium* and *Streptococcus* (Britz *et al.*, 1988; Chynoweth & Pullammanappallil, 1996; Iannotti *et al.*, 1982).

Acetogens

The end-products of acidification can be utilised as an energy source by acetogenic bacteria at this stage of the metabolic pathway of the digestion process to form fermentation products. These fermentation products primarily include H_2, CO_2, formate and acetate. Odd-numbered carbon skeletons may also lead to the production of other fatty acids and metabolites such as propionate, butyrate, lactate, succinate and alcohol (Zinder, 1990). Acetogenesis occurs only if the H_2 concentration in the digester is very low. Therefore, acetogens can only grow if H_2-reducing bacteria are present, distinguishing them from homoacetogens. Genera include *Syntrophobacter, Syntrophomonas* and *Syntrophus* (Atlas, 1997; Iannotti *et al.*, 1986).

Homoacetogens.

Homoacetogenic bacteria are those bacteria responsible for the conversion of formate or H_2 and CO_2 into acetate. They also have the capacity of fermenting monosaccharides to acetate without generating H_2 or CO_2 (Braun *et al.*, 1979;

Ohwaki & Hungate, 1977). Genera include *Clostridium, Acetobacterium, Acetoanaerobium, Acetogenium, Eubacterium* and *Butyribacterium* (Zinder, 1993). The significance of these bacteria in the AD process is not yet fully understood and it is generally accepted that they can donate hydrogen to methanogens through a phenomenon known as interspecies hydrogen transfer.

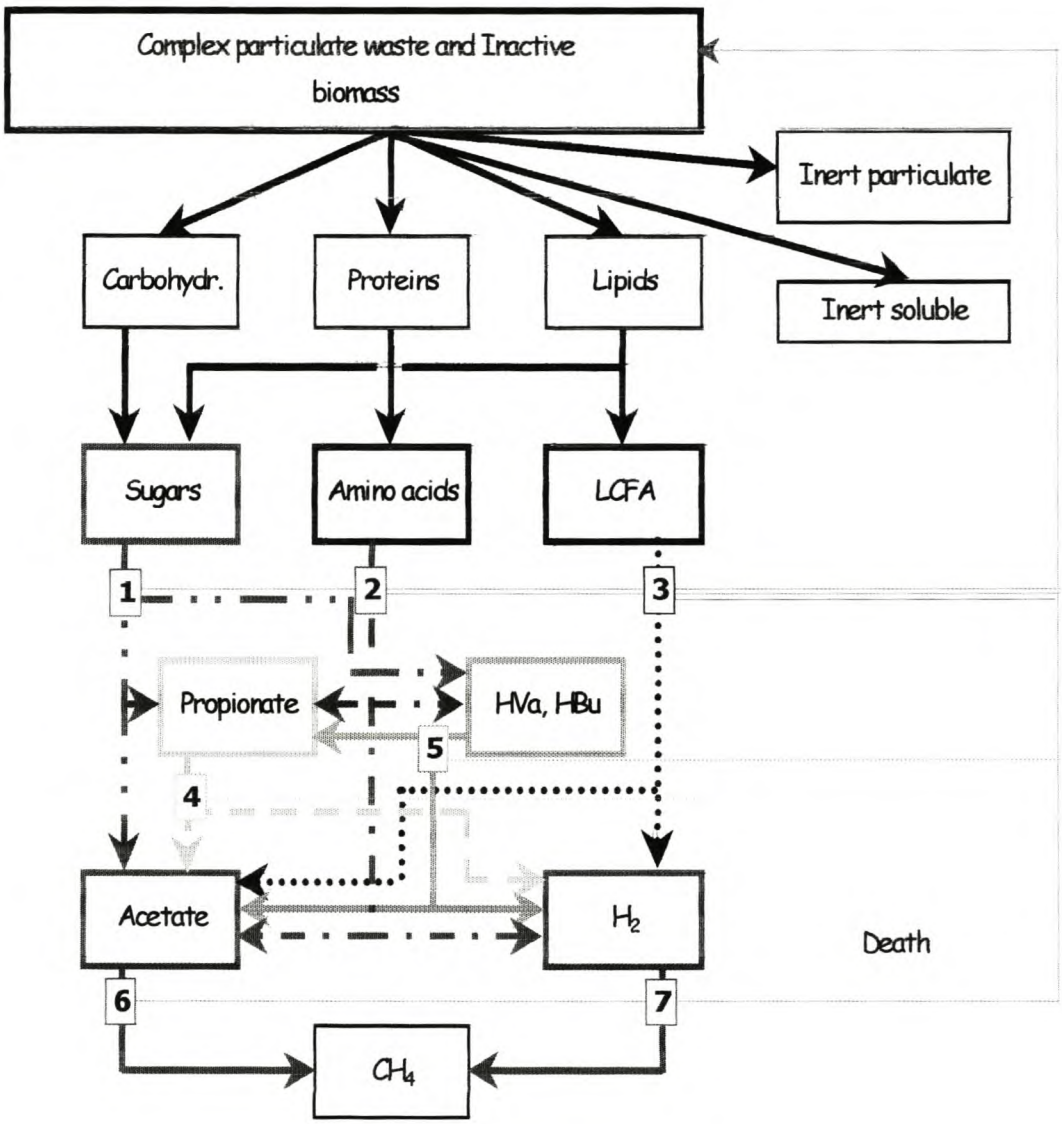

Figure 1. The biological processes implemented in AD 1: (1) Acidogenesis of sugars, (2) Acidogenesis of amino acids, (3) Acetogenesis of LCFA, (4) Acetogenesis of propionate, (5) Acetogenesis of butyrate and valerate, (6) Acetotrophic methanogenesis, and (7) Hydrogenotrophic methanogenesis (International Water Association Task Group, 2001).

Homoacetogenic bacteria have highly efficient hydrogenases. The affinity of these enzymes for their substrate is sufficiently high to maintain an exceptionally low H_2 partial pressure when active methanogenesis is occurring. They also contribute to maintain low hydrogen partial pressures during perturbations that temporarily inhibit the methanogens (Varnam & Evans, 2000).

Methanogens

The last group participating in the anaerobic conversion process is the methanogens. Considering that they are the key organisms in this process, this unique bacterial population will be discussed in more detail.

E. THE METHANOGENS

Methanogenesis occurs in a wide variety of anaerobic environments such as fresh water and marine sediments, peat bogs, sludge digesters, the intestinal tract of animals especially ruminants, and anoxic waters (Lederberg, 1992). Methanogens are unicellular organisms originally thought to be bacteria but now recognised as belonging to a separate phylogenetic domain, the archaea. Methanogens are also obligate anaerobes that will not even tolerate brief exposures to oxygen. They have an incredible metabolism that can use H_2 as a sole energy source and CO_2 for cell carbon synthesis. Several species utilise formate, but relatively few ferment acetate and methylamines and one species, *Methanosarcina bakeri,* can use methanol. Another metabolic feature shared by several species is the ability to synthesise all cellular carbon from CO_2 while growing at the expense of hydrogen oxidation (Atlas, 1997; Taylor, 1982; Zeikus, 1977). In the process of making cell material from H_2 and CO_2, the methanogens produce CH_4 in an unique energy-generating process. The end-product, methane, then accumulates in their environment. It is generally said that methanogen-metabolism created most of the natural fossil fuel reserves that are now readily tapped as energy sources for domestic or industrial use. Methane is a significant greenhouse gas and is accumulating in the atmosphere at an alarming rate (Anon., 1997).

Methanogens represent a microbial system that can be exploited to produce energy from waste materials. Large volumes of methane are produced

during industrial sewage treatment processes, but the gas is usually wasted rather than tapped for recycling. It has been well established that acetate is the major methanogenic precursor. Other substrates include formate, methanol, H_2 and carbon monoxide (Atlas, 1997; Zeikus, 1977).

Few natural groupings of micro-organisms are as morphologically diverse as the methanogenic bacteria. Nevertheless, all methanogenic species share certain unique and unifying physiological properties. Methanogens should no longer be regarded as a mysterious group of poorly studied microbes. Indeed, the present 'world energy crisis' has generated a new stimulus and scientific interest to better understand bacteria that produce natural gas (Atlas, 1997; Zeikus, 1977).

Properties and characteristics

The methanogenic bacteria can be either Gram-positive or Gram-negative, long or short rods, cocci or sarcinae and mycoplasma forms have also been discovered. This morphological diversity led to their initial classification throughout the major bacterial groups (Taylor, 1982). However, their unique physiology led Barker (1936) and Bryant (1976) to classify methanogens into a single family, the *Methanobacteriaceae.* The paradox was been resolved by following the application of sequencing techniques to the 16S ribosomal RNA of many kinds of bacteria, including the methanogens. This technique is based on the identification of organisms using their 16S rRNA to determine the association coefficient, S_{AB}. The higher the S_{AB} value of two organisms, the greater the similarity of the sequence of the 16S rRNA of the organisms (Taylor, 1982).

Metabolic activity

Methanogenesis is a strictly anaerobic respiratory means of metabolism that produces cellular energy in the form of ATP through the reduction of CO_2, CO, formate, methanol, methylamines, or acetate to CH_4 (Atlas, 1997; Balch *et al.;* 1979; Blaut, 1994; Taylor, 1982; Zinder, 1990). During this process methane is produced, as the product of the energy-generating metabolism of methanogens. Methanogens can only use a small number of simple compounds, most of which contain only one carbon. Many methanogens use only one or two substrates, with the greatest versatility represented in some strains of the genus *Methanosarcina*,

which can use seven substrates. *Methanosarcina* can generate methane from methanol, and from mono-, di- and trimethylamines. The metabolic pathways of methanogens can be divided into three categories: CO_2-reducing, methylotrophic and aceticlastic pathways (Fig. 2) (Atlas, 1997).

CO_2-reducing methanogenesis

Most methanogens can oxidise hydrogen and reduce CO_2 to produce methane. In this CO_2-reducing methanogenic pathway, CO_2 is the electron sink (that is the molecule being reduced to the methyl level) and H_2 is the major electron donor substrate. The CO_2-reducing pathway uses a series of four two-electron reductions to convert CO_2 to methane. Most methanogens have a hydrogenase enzyme that splits molecular H_2. By this action, the methanogens can support growth by using H_2 as a source of electrons for the reduction of CO_2 (Blaut, 1994).

Many H_2-using methanogens can also utilise formate as an electron donor for the reduction of CO_2 to methane. Formate is used as substrate after it is first oxidised to H_2 and CO_2 (Blaut, 1994)

The reduction of CO_2 to CH_4 occurs via a series of reductive steps that generate a methyl group. This pathway requires several reducing enzymes and co-enzymes that are unique to methanogens. These include the co-enzymes F_{420} and the nickel-containing co-enzyme F_{430}, methanofuran, methanopterin and co-enzyme M (Nyns, 1983). Carbon dioxide is fixed initially to the co-factor methanofuran to produce formyl-methanofuran. To accomplish this reaction, co-enzyme F_{420} accepts two electrons from H_2 or NAPDH. The oxidised form of co-enzyme F_{420} has a characteristic blue-green fluorescense at 420 nm. Methanofuran, the initial acceptor of CO_2, is reduced to a formyl group using electrons from co-enzyme F_{420} from the first step of methanogenesis. The formyl group is passed to methanopterin and carries the C_1 group in its reduction from formyl through methenyl to methyl carbon. The methyl group is transferred to CoM to form CH_3-S-CoM, which is the substrate for methyl reductase (Blaut, 1994; Nyns, 1983). The methyl group is further reduced to yield methane with electrons donated from 7-mercaptoheptanoylthreonine phosphate (HS-HTP). In the last

METABOLIESE BANE

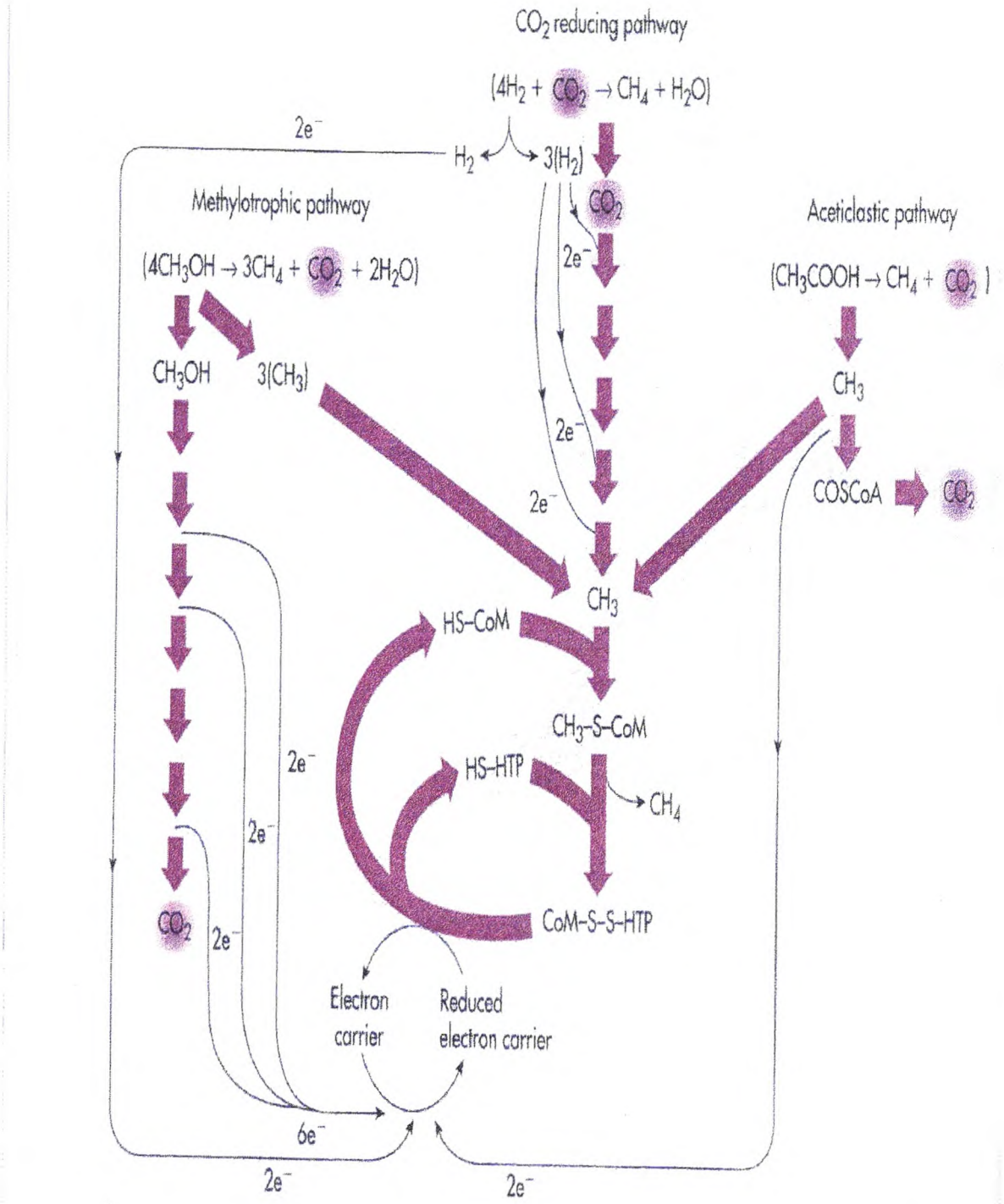

Figure 2. Three metabolic pathways used by methanogenic bacteria to produce methane and CO_2 (Atlas, 1997).

step of methanogenesis, as the methyl group is reduced to methane, a proton is pumped to the outside of the membrane to establish a proton motive force. This force drives the synthesis of ATP via a membrane-bound ATPase. The conversion of CO_2 to methane is an exergonic reaction with a ΔG^o of -31 kcal.mole^{-1} (Zinder, 1993)

Methylotrophic methanogenesis

During methanogenesis, compounds that contain methyl groups, such as methanol, are also utilised. The methyl groups are reduced to methane by a methyl reductase. Electrons for this reaction may be obtained by oxidising a fraction of the methyl groups to CO_2 or by using H_2 as an electron donor. Methyl groups are transferred to HS-CoM to form CH_3-HS-CoM, which becomes the electron acceptor. Another methyl group from methanol or methylamine is activated and oxidised to CO_2 via the reversal of the pathway, formylmethanofuran being the terminal reaction. Thus, methylotrophic groups from three CH_3OH molecules serving as electron acceptors for the six electrons generated by the oxidation of one CH_3OH to CO_2. (Atlas, 1997; Zinder, 1993).

Aceticlastic methanogenesis

A few methanogens can generate methane from acetate using a fermentative pathway that is called aceticlastic methanogenesis (Fig. 2). Methanogenesis from acetate is a major source of methane produced in sludge digesters (Zinder, 1993). In this pathway, acetate is activated to acetylphosphate by ATP-driven acetate kinase and acetyl-CoA is then formed by a phosphotransacetylase. The acetyl-CoA serves as the substrate for carbon monoxide dehydrogenase. This nickel/iron-sulphur protein forms a methyl-group, a carbonyl group and HS-CoA. A second component of the carbon monoxide dehydrogenase complex is a corrinoid-containing iron-sulphur protein that accepts the methyl group generated by the nickel iron-sulphur protein and donates it either to form 5-methyl-H_4MPT or directly to produce HS-CoM. The CH_3-S-CoM formed in this manner serves as the substrate for methylreductase to produce methane (Atlas, 1997; Nyns, 1983).

The principal methanogenic reactions as summarised by Chynoweth (1992) include the following:

Substrate	Conversion reaction	$\Delta G^{o'}$ (kJ/mol CH_4)
• Hydrogen:	$4H_2 + CO_2 \rightarrow CH_4 + 2H_2O$	-130.4
• Formate:	$4HCOOH \rightarrow CH_4 + 3CO_2 + 2H_2O$	-119.5
• Acetate:	$CH_3COOH \rightarrow CH_4 + CO_2$	-32.5
• Carbon monoxide:	$4CO + 5H_2O \rightarrow CH_4 + 3H_2CO_3$	-185.6
• Methanol:	$4CH_3OH \rightarrow 3CH_4 + CO_2 + 2H_2O$	-112.5
• Monomethylamine:	$4(CH_3)NH_2 + 2H_2O \rightarrow 3CH_4 + CO_2 + 4NH_3$	-74
• Dimethylamine:	$2(CH_3)_2NH_2 + 2H_2O \rightarrow 3CH_4 + CO_2 + 2NH_3$	-74
• Trimethylamine:	$4(CH_3)_3N + 6H_2O \rightarrow 9CH_4 + 3CO_2 + 4NH_3$	-74
• Methyl mercaptans:	$2(CH_3)_2S + 2H_2O \rightarrow 3CH_4 + CO_2 + H_2S$	-

F. ANAEROBIC DIGESTION IN PRACTISE

Operational parameters

High-solid waste vs. low-solid waste

Anaerobic bioconversion can, at present, be divided into two types of processes: low-solid processes (less than 10% (m/m), typically 4 to 8% (m/m)) and high-solid processes (25 to 32% (m/m)). The low solids are the most commonly used anaerobic digestion process, especially for the treatment of wastewater sludges. The high-solids anaerobic process is a more recent development (Kayhanian & Tchobanoglous, 1993). The application of high-solid fermentation technology offers improved economics over the more traditional low-solid fermentation process. An important benefit of the high-solids process is the reduction in process water, which results in smaller fermentation reactors, and thus lower capital and operating costs. Rivard *et al.* (1993) concluded that the level of bulk reduction in a high-solid digestion system was substantially greater than that of the low-solids system.

Inoculation

The quality and quantity of the inoculums are critical for the production of methane during anaerobic digestion. Low inoculum levels may lead to digestion failure due to the more rapid growth of acid-forming bacteria compared to the methanogens. This will lead to a rapid depression of the system pH. Depending

on the alkalinity, a digester may be able to recover and stabilise. In conventional digesters, the inoculum-to-feed ratio is typical greater than 10. In digesters where washout of critical organisms is a concern, suspended solids in the effluent may be settled and recycled (Chynoweth *et al.*, 1991; Chynoweth *et al.,* 1993). For the digestion of solid wastes, different kinds of inocula have been used such as cattle manure, anaerobic sludge or anaerobic compost from a previous run (Stroot *et al.*, 2001).

Nutrients

Nitrogen and phosphorus are the major nutrients required for anaerobic composting. Studies conducted by Kayhanian (1993) showed that a C:N ratio of 25 is critical for successful anaerobic digestion above which nitrogen becomes limiting. Kayhanian (1993) also reported that the optimum NH_3-N concentration in high solids anaerobic digestion sould be at least 700 $mg.l^{-1}$. Ammonia plays an important role in the buffering capacity of digesters, but may be toxic to the process at concentrations above 3 000 $mg.l^{-1}$. Other nutrients needed in intermediate concentrations include sodium, potassium, calcium, magnesium, chlorine and sulphur. Micronutrients required include iron, copper, maganese, zinc, nickel and vanadium (Fujishima *et al.,* 2000; Speece, 1987).

Temperature

Three temperature optima are important when considering AD as an industrial treatment option. These are the psychrophilic (> 60°C), mesophilic (30° - 40°C) and moderate thermophilic (50° - 60°C) temperatures. Recent studies by Lepistö & Rintale (1996) also demonstrated that anaerobic digestion is possible at temperatures up to 80°C (Van Lier *et al.,* 2001). Bacterial populations in thermophilic digesters exhibit some differences when compared to mesophilic digesters. Although methanogenic conversions can occur at high temperatures, temperatures between 50° and 60°C are generally the standard for thermophilic AD treatments as higher temperatures can result in unstable AD processes. At these temperatures thermophilic digestion has been reported to be just as stable as mesophilic digestion (Ahring *et al.*, 2001). In some cases, ammonia concentrations higher than 4 000 $mg.l^{-1}$ will affect the performance of thermophilic processes, due to toxicity problems (Ahring, 1994). In general, the kinetics of the

digestion processes doubles for every 10°C increase in operating temperature. This however, will take place up to a critical temperature of 60°C when a rapid drop in the microbial population occurs (Harmon *et al.*, 1993). During thermophilic temperatures acetate is oxidized by a two-step mechanism but when mesophilic temperatures apply, acetate is converted to methane through the acetoclastic mechanism of direct conversion (Ahring, 1995).

The benefits of thermophilic processes, a greatly increased rate and a high sanitizing effect compared to mesophilic temperatures, have, however, often been set against a lower degree of stability and therefore, a higher concentration of volatile fatty acids (Wieant, 1986). Also, the concentration of free NH_3 is higher under mesophilic than termophilic conditions, leading to higher toxicity problems.

Increasing the temperature during AD to higher than 60°C will often result in an increased production of volatile fatty acids (VFA). At this temperature range, the activity of bacteria, such as propionate and acetate degrading bacteria, has been shown to decrease. From the above information it can be concluded that temperature strongly affects the microbial populations present in AD systems and thus the rate of bioconversion (Van Lier *et al.*, 2001).

Performance parameters

Methane production and decomposition of organic matter

The production of methane is directly related to the rate and extent of the conversion of organic matter, which is expressed as VS (volatile solids) or COD. The use of VS and COD allows for the calculation of the reduction in organic matter.

The methane production rate is often used as a measure of process kinetics and is the direct product of the loading rate ($kg.m^{-3}.day^{-1}$) and methane yield ($m^3.kg^{-1}$ VS). Biogas production can occur at total solid concentrations of up to 40% (m/m), loading rates of 21 kg $COD.m^{-3}.d^{-1}$ and methane yields of 0.50 $m^3.kg^{-1}$VS (Molnar & Bartha, 1988). The methane content of biogas is often considered as a good indicator of the stability of anaerobic processes (Owens & Chynoweth, 1993).

Organic acids, pH and alkalinity

Anaerobic digestion is usually performed at neutral pH conditions (pH 6.5 – 8.0). Toxicity under low pH conditions is usually associated with the presence of undissociated VFA.

Anaerobic digestion can occur at pH conditions as low as 4.5 to 5.0, provided that no VFA's are present. Process pH results from the interaction of the carbon dioxide-bicarbonate buffering system present with the VFA and ammonia formed during the process (Nel & Britz, 1986). It is important that sufficient buffering capacity for the acids produced exist, in order that the acids will not lower the pH to a level where they impact the microbial consortium (Price, 1985). Anaerobic treatment under acidic or alkaline conditions may prove to be valuable in the future especially when industries demand processes with a higher tolerance for extreme conditions (Van Lier *et al.,* 2001).

Under conditions of overloading and the presence of inhibitors, methanogenic activity cannot remove hydrogen and organic acids as rapidly as they are produced. This results in the accumulation of VFA's, depletion of buffer and a rapid drop in pH. VFA levels of >10 000 $mg.l^{-1}$ is considered as critical for anaerobic digesters. If this is not corrected through pH control and reduction in feeding, the pH will drop to levels where fermentation is not possible (McMahon *et al.,* 2001). The presence of VFA's such as propionic acid and higher molecular weight acids, are an indication of the onset of digester failure (Ahring, 1995; Hill & Holmberg, 1988).

Ammonia and bicarbonate are the major alkalis contributing to the alkalinity during digestion. A normal volatile acid to alkalinity ratio is 0.1. Ratios in the range of 0.5 indicate the onset of failure and a ratio of 1.0 and above are associated with total digester failure (Ahring, 1995).

G. COMMERCIALISATION AND PRODUCT USE

The commercial application of AD to treat solid waste is just beginning to emerge as several barriers to commercialisation still exist. One of these barriers is that landfilling currently presents an ideal solution for disposal of solid waste because of the lower disposal costs. However, as liabilities and lack of public acceptance of landfills increase, anaerobic digestion will become a more attractive option.

Biogas

During AD a mixture of CH_4 and CO_2 (biogas), is produced. Biogas is similar to 'natural gas' but has higher methane content, making it an excellent fuel for certain uses. The composition is generally 55% methane and 45% carbon dioxide, with traces of hydrogen, hydrogen sulphide and water vapour (Anon., 1997; Constant *et al.,* 1989; Tafdrup, 1994). The composition of biogas is dependent upon the characteristics of the feedstock being used, hydraulic retention time and the physico-chemical conditions operational during digestion (Earle *et al.;* 1991; Christensen & Hjort-Gregersen, 1994).

Biogas offers a great deal of flexibility with respect to its use. A net energy surplus of 165 to 245 $kWh.ton^{-1}$ of solid waste treated can be generated in the form of electricity (De Baere, 2000). This gas is combustible without purification and can be used directly for heating, cooking, running generators and internal combustion engines. These uses often require some passage through a condensation trap to reduce the water content. Biogas can also be upgraded by the removal of carbon dioxide and hydrogen sulphide and compressed for use in motor vehicles or distribution into gas pipelines (Chynoweth & Pullammanappallil, 1996; Constant *et al.,* 1989; Lusk, 1998). A typical plant treating the municipal solid wastes from a population of 100 000 in the USA could be expected to generate about 50 000 m^3 of $CH_4.day^{-1}$ (Chynoweth, 1996).

Biogas is a renewable energy source. When replacing fossil fuel, the CO_2 greenhouse emissions are reduced. (Husted, 1992). Emissions of N_2O might also be reduced, since less denitrification occurs in the soil when digested slurry is applied (Ørtenblad *et al.*, 1992).

Compost as a soil conditioner

A number of agricultural and environmental advantages of bioconversion have been identified if farmers and food processing industries are joined together in co-digesting organic wastes with manure. The mixing of manure and solid food wastes has an improving effect on the quality of the compost as fertilizer (Lusk, 1998). In principle, the utilisation of compost could serve various aims:

- Part of growth substrates;
- Soil replacement and soil improvement;

- Fertilization;
- Improvement of soil fertility; and
- Protection against erosion (Vogtman *et al.*, 1996).

Today, the positive influence of compost on soil fertility is undisputed and therefore, the utilisation of compost as a substance for soil improvement is widespread. Compost has a high quality standard and due to its determining characteristics it can be profitably used in optimal quantities in all fields of crop management (Vogtman *et al.*, 1996).

One unknown advantage of compost is the unique opportunities it offers to examine fundamental interactions between plant pathogens, biocontrol agents and plant roots. Compost has the potential to provide consistent biological control of plant diseases. Foliar as well as root pathogens are affected by compost and are suppressed by a phenomenon called microbiostasis (Hoitink, 1996).

The use of compost in the agricultural sector also presents financial advantages as less money is spent on buying chemical fertilizers. During anaerobic digestion, pathogens and weed seeds are killed and the reduction of odours lead to a reduction in flies around farms where compost is applied. The co-digestion of manure and food wastes can lead to improved fertilizer utilization and less chemical fertilizer consumption. This is an aspect of increasing environmental importance as can be seen from the more stringent regulations stated in the National Water Act No. 36 of 1998, which were put forward in order to protect surface and ground water from pollution. More efficient fertilisation results in less nutrient loss and consequently less water pollution from nutrients (Tafdrup, 1994).

The ability to utilise compost as a soil conditioner depends on its agronomic characteristics and pollution potential, which can be further classified as physical characteristics, chemical characteristics and biological characteristics. Anaerobic compost can be spread directly onto farmland or be dewatered to provide separate liquid fertiliser and solid compost products. In most cases, anaerobic compost undergoes a curing or pre-treatment stage where the compost is aerobically matured to provide a compost substitute (Anon., 1997). Typical characteristics for compost as summarised by the SEBAC group (Anon., 1997) include:

- Water holding capacity of 35% which is controlled by drying time;

- Dark brown colour;
- No odour coming from the compost;
- C/N/ ratio of 15 to 20%;
- Suitable K, P and N content for agricultural applications;
- pH between 6 and 7; and
- Organic matter content of 50%.

Advantages and disadvantages of bioconversion

Advantages

The advantages offered by AD are numerous, making this process not only an excellent management system, but also a powerful alternative to fossil fuel, chemical fertilisers, electricity and heating systems to name but a few. Owing to the large amount of surplus energy produced in the form of biogas during the AD of solid waste, considerably larger amounts of fossil fuels can be substituted. Methane is a very combustible gas and in its purified form it can be used to power vehicles and other machines running on fuel. This appears to be a very feasible advantage as South Africa is facing the increasing costs of petrol and diesel caused by the increasing unavailability of crude oil (Lusk, 1998).

Although landfilling can also be seen as an anaerobic treatment process, it differs a great deal from AD of solid wastes as described in this thesis. The concerns around landfilling are not to be dismissed. Landfill sites are polluting valuable groundwater and can be seen as a health hazard as they provide a place for breading to flies and vermin (Pagilla *et al.*, 2000). Anaerobic digestion provides a solution to these problems, as it is not a process that is left uncontrolled in nature as the case in landfills. Anaerobic digestion is a highly specialised treatment option that does not contribute whatsoever to any of these problems stated above (Pagilla *et al.*, 2000).

Greenhouse gas emissions from landfill and incineration sites are causing great harm to the environment and also contribute greatly to the aspects of global warming. The earth is facing the danger of warmer temperatures as greenhouse gasses are forming a layer around the earth, preventing it from cooling down (Anon., 1997). The anaerobic treatment of solid wastes is performed in closed construction facilities. These facilities are well equipped to prevent methane from

polluting the air as this valuable gas is collected for other uses (Parker *et al.*, 1981).

Anaerobic bioconversion can be performed within densely populated urban areas and even mega-cities. This will lead to reduced transportation, thus having an additional positive effect on the financial aspects that municipalities are continually facing when concerned with waste management. Anaerobic systems can also be the starting point for intensification of urban agriculture and tree-planting programmes (Pagilla *et al.*, 2000).

The positive impact that AD has on the environment can be further acknowledged by the use of compost from anaerobic processes instead of the use of chemical fertilizers. Continuous use of chemical fertilizers will, in the long run, leave the soil more depleted of nutrients and precious organisms than it was before. It has been shown that compost can improve soil quality (Lusk, 1998).

When operated correctly, AD of solid waste would not leave unpleasant smells and a volume reduction of 50% and more can be expected (Anon., 1997). In other words, the waste that was fed to the digester will be reduced to such a way that only half of what was put in will come out at the end. What is more, this half is not waste anymore, it is a valuable soil conditioner (Anon., 1997).

Other advantages:

- Good solids stabilisation;
- provides a source of employment in developing countries;
- relative low capital investment; and
- low operating and maintenance costs (Anon.,1997).

Disadvantages:

Disadvantages as summarized by O'Keefe *et al.* (1993) and Parker *et al.* (1981) are:

- Initial start-up time for AD is very long;
- Pre-treatment is necessary in most cases. Waste either has to be sorted to be uniform, or has to be shredded into smaller pieces;
- Few full-scale plants treating solid wastes exist, as the AD of solid waste still needs to be further explored; and

- AD processes are sometimes regarded as unstable. The reasons for instability are not yet fully understood, as the anaerobic process is very complicated.

H. ECONOMICAL ASPECTS OF ANAEROBIC COMPOSTING AS A POTENTIAL TREATMENT OPTION

AD of solid wastes has in recent years become a mature technology, as many developments have occurred both at the research and industrial level. De Baere (2000) reported that more than 1 million tones of organic wastes are digested annually in Europe and this is increasing each year. An increase in capacity of 200 kton is expected in 2001 (De Baere, 2000). This waste is converted to a valuable biogas on the one hand and to a stabilized residual matter on the other hand. Biogas is presently selling for 14 to 21 Euro.ton^{-1} in Europe, which equals between R 95 and R 142 (De Baere, 2000). Obviously, financial means in developing countries are limited and in recent years it has often been experienced that international firms are offering financial support to these countries. However, due to urbanisation more local companies are investing in anaerobic digestion, as there is an increased demand for a solid waste treatment option with minimum space requirements (Van Lier *et al.*, 2001).

Operational costs for industrial or even pilot-scale plants treating solid waste anaerobically mainly depend on the costs of energy within a short-term perspective. Presently, anaerobic treatment of solid waste is more expensive than landfills if emissions are not accounted for, and far less cost intensive than incineration plants (Verstraete, 2000).

The costs involved in AD are more or less a factor 1.2 – 1.5 higher than for aerobic composting. This figure can, however, change as legislation and restrictions become more stringent to prevent harmful emissions from waste treatment facilities. For the near future it is expected that the AD treatment of waste will keep a position of being more costly than other treatment options. Looking at the broader picture, this will change in time as biogas is becoming more and more important and as landfill sites close (Van Lier *et al.*, 2001).

I. THE FUTURE

Over the last decade, much progress has been made in the AD treatment of solid waste including advances in research and development, construction of new plants and more favourable legislation. In the future, the AD of solid waste will become a major role-player in better waste management (Van Lier, 2001). A number of aspects, however, still need to be taken into further consideration like the temporary emission of methane when anaerobic digested compost undergoes further aerobic treatment (Edelmann *et al.,* 1999).

As AD is being explored each passing day, this powerful treatment option is receiving more attention due to its obvious advantages and broader applications. Co-digestion of different kinds of solid and semi-solid wastes is promising to be a valuable treatment option in the near future. The final objective of co-digestion would be to produce compost that can be recycled as a soil-conditioner. Combining wastes will further leave the possibility of treating wastes that cannot be anaerobically treated on their own (Van Lier, 2001).

Another aspect that particularly deserves to be further explored is the capacity of AD to decompose chlorinated organics and thus achieve a putative decontamination of organochlorines (Christiansen *et al.,* 1995). One problem that the food processing industry has to face is the fate of micro-pollutants, like polyphenols, PCB's and dioxins and the overall end-product quality. In this regards, AD offers specific advantages. Pre-treatment of wastes are important to the overall success of an AD process. Continuous studies of the microbiology and physiology of anaerobic micro-organisms will enable AD scientists to have a better understanding in finding the right blend of mechanical, chemical and enzymatic pre-treatment options (Van Lier *et al.,* 2001).

The most advantageous contribution of AD is probably the production of biogas. As environmental regulations become more stringent, it is necessary to look at other alternatives as fuel, electricity and other forms of energy. Biogas can be used for heating, the generation of electricity, be upgraded to 90% methane for the use as fuel in vehicles or sold as gas. Compared to other fuels, methane is known to be less polluting (Anon., 1997).

Creating a clean and healthy environment for young and old, forms the basis of socio-economic stability. Waste treatment and management is not just a

matter of technology, economy and ecology, but also very much a matter of social perception. Hence, similar to the fact that we keep our body clean and healthy, we will inevitably also become less tolerant towards 'dirtying' the systems that is in reality 'us' (Verstraete, 2000).

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CHAPTER 3

DETERMINATION OF OPERATIONAL PARAMETERS FOR ANAEROBIC COMPOSTING OF SOLID WASTE FROM THE FRUIT PROCESSING INDUSTRY

Abstract

The anaerobic digestion of solid wastes from the fruit processing industry is becoming more attractive as a solution to the solid waste problem because of its obvious advantages (reusable biogas and valuable compost). To have a functional composting system, the objective must be to develop strategies to identify and control the best operational parameters.

In this study three different experimental studies were performed to achieve this objective. Several important lessons were learnt. The first was that a mechanical mixing action was not necessary, because the anaerobic composting process, with apple pomace as substrate, can successfully proceed without any mixing. The strict control of specific operational parameters (pH, inoculum, moisture level, moisture value, VFA production and VFA removal) during the anaerobic composting process is of great importance when optimisation of the process is to be considered.

The inoculum ratio and sort of inoculum are of great importance during the digesting process, as it was found to be directly responsible for the microbial community necessary to digest the pomace. It was concluded that the inoculum and thus the microbial population, was responsible for the production of biogas early in the composting process when the acidogenic bacteria are still dominantly active. The data also showed that small inoculums would not be active enough to start the digestion process. On the other hand, a too large inoculum will have an important negative economical impact when the process is scaled-up.

In this study large concentrations of volatile fatty acids were produced during certain of the composting studies and these were found to be the cause of bad digester failures when not removed or neutralised in time. Propionic, butyric and acetic acids were the major acids produced. It was concluded that these acids caused the pH to drop dramatically and led to acidic situations. By removing the leachate and using it as a substrate in an UASB bioreactor and then re-

inoculating into the composting units helped to solve this problem as well as the pH control situation.

Another aspect that was identified as an operational parameter that had to be carefully controlled and optimised was the moisture content. Different 'moisturising liquids' were evaluated and data showed that UASB bioreactor effluent was the best 'moisturiser' to use. The moisture content (%) in the digestion units was also identified as an important parameter to take into consideration. In the studies it was found that better results were obtained when the moisture content at start-up was higher (60% or higher (m/m)).

Introduction

Fruit and vegetable processing industries, especially juice producing plants, generate large volumes of solid waste each season. The moisture content of these wastes can be as high as 80% (m/m), which presents a problem when it comes to traditional disposal options (Kim *et al.,* 2000). At present, the disposal options for these wastes are restricted and without any obvious advantages, which makes these plants potential candidates for the newer anaerobic composting technology (Du Randt, 2000).

Considerable interest has been shown in the application of anaerobic digestion as a method to treat wastewaters from the food processing industry (Britz *et al.*, 2000; Trnovec & Britz, 1998). Anaerobic digestion technology has reached a point where organic solids can be used as a suitable substrate with obvious advantages such as the production of biogas and a fertilising, compost by-product (De Baere & Verstraete, 1984). There are a number of factors, including degradability, pH, temperature, microbial community composition and quality, and the composition and concentration of the substrate, which may impact the biogas production efficiency. Thus, rational management of the process requires the determination and optimisation of the most important operational parameters (Molnar & Bartha, 1989).

It is generally known that wastes with total solid (TS) concentrations of up to 30% (m/m) can be readily used as substrate, without inhibition by volatile acids, for the anaerobic composting process (Wujcik & Jewell, 1980). However, the

buffering capacity of the bioreactor contents, relative to pH control at a required level, must be maintained by the addition of lime (Buivid & Wise, 1981).

There are several advantages of the anaerobic digestion of solid wastes with a high solids concentration. The reduction in volume can be significant if the substrate being used is not drastically diluted (Molnar & Bartha, 1989). The use of anaerobic digestion of solid waste has already been shown to be successful with the use of tomato, a mixture of mango, pineapple, banana and orange solid wastes, and even municipal solid wastes, as substrate (Hills & Nakano, 1984; Rivard *et al.,* 1995; Viswanath *et al.,* 1992).

The aim of this study was to develop a laboratory scale system for the anaerobic treatment of fruit solid wastes. Operational parameters, that show significant control possibilities, will be identified and optimised during the process.

Material and methods

Anaerobic composting units

In this study, modified 2 L glass containers, as illustrated in Fig. 1, were used as composting units. A layer of glass wool (Lasec, Cape Town) was placed in the bottom of each unit to serve as a filter to prevent the fruit solid waste from clogging the leachate outlet. Moisture was added through the cap opening. Biogas exited via a glass extension on the upper side, while the leachate was removed through a glass extension at the bottom of the unit. A third glass extension was used to flush the system with nitrogen. The compost units were incubated at 35°C at all times.

Substrate and inoculums

Apple pomace was obtained from Appletiser, Grabouw, for the purpose of this study. The pomace was frozen in plastic bags and stored at –18°C until needed. Sludge was collected from the Kraaifontein Municipal Works and stored at 4°C. Boland Mushrooms, Worcester, provided the mushroom compost. The Efekto Organic Compost Activator was purchased at the Agrimark, Stellenbosch.

Analytical methods

The following parameters were monitored according to Standard Methods (APHA, 1992): pH and Chemical Oxygen Demand (COD). The total solids (TS) were analysed according to Official Methods of Analysis (AOAC, 1990).

Volatile fatty acid (VFA) concentrations were analysed using a Varian (Model 3700) gas chromatograph equipped with a flame ionisation detector and a 30 m Fused Silica capillary column with a 007 bonded FFAP stationary phase (Quadex Co., New Haven). The column temperature commenced at 105°C for 2

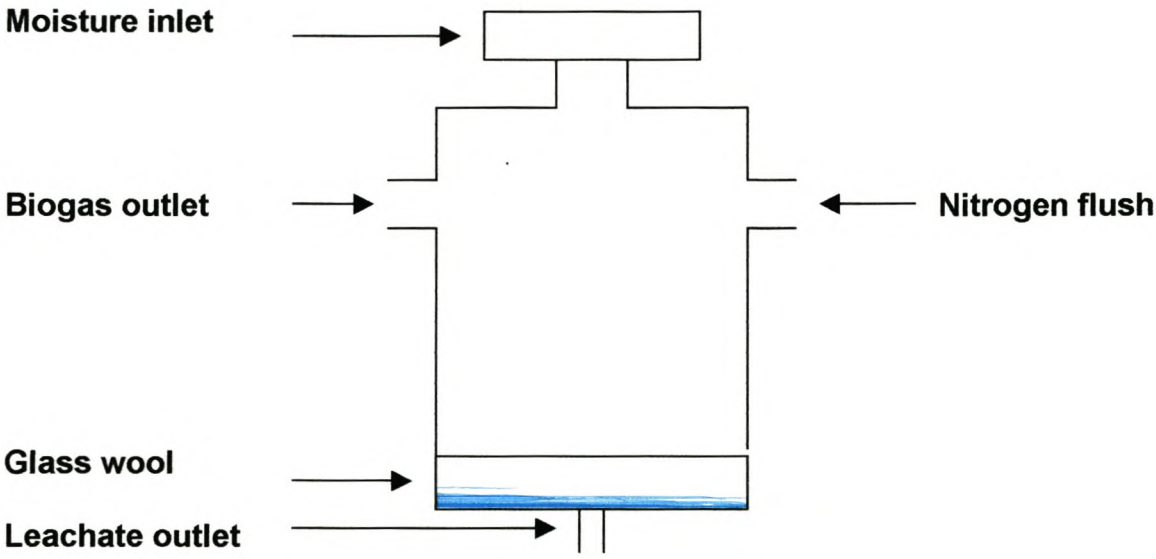

Figure 1. Modified 2 L glass container used as anaerobic composting unit for the digestion of fruit solid waste.

min. and then increased to 190°C at 10°C per min and the total running time was 25 min. The detector and inlet temperatures were set at 300°C and 130°C, respectively. Nitrogen gas was used as the carrier gas (flow rate: 6.1 $ml.min^{-1}$).

The biogas composition was determined using a Fisions (Model 3 700) gas chromatograph equipped with a thermal conductivity detector and a 2.0 m x 2.0 mm i.d. column packed with Hayesep Q (Supelco, Bellefonte, PA), 80/100 mesh. The oven temperature was set at 45°C and helium was used as the carrier gas (flow rate: 40.0 $ml.min^{-1}$).

UASB Bioreactor

In this study, a laboratory-scale upflow anaerobic sludge blanket (UASB) bioreactor with an operational volume of 700 ml was used. The design combined an UASB system with an open gas/solids separator at the top of the bioreactor. The gas exited the system via the top, while the substrate was introduced at the bottom of the bioreactor. The overflow was drained through a U-shaped tube to prevent any atmospheric oxygen from entering the system. The bioreactor was kept in an incubation room where the temperature was maintained at 35°C, because the bioreactor was too small to fit with a heating tape. The substrate was fed semi-continuously by means of a peristaltic pump, which was connected to an electronic timer. The reactor was seeded with granules obtained from a full-scale UASB bioreactor treating brewery effluent. The granules were re-activated by circulating a urea and K_2HPO_4 (500 $mg.l^{-1}$ each) mixture through the reactor for 3 d. After that the bioreactor was fed with water supplemented with 10 $g.l^{-1}$ sodium lactate, 500 $mg.l^{-1}$ K_2HPO_4, 500 $mg.l^{-1}$ urea, 1 $g.l^{-1}$ glucose, 20 $g.l^{-1}$ yeast extract and 1 $ml.l^{-1}$ trace elements (Britz *et al.,* 2000; Trnovec & Britz, 1998). The pH was adjusted to 7.5 and the hydraulic retention time (HRT) was set at 24 h and then steadily decreased to 19 h. The substrate was then systematically replaced with leachate removed from the anaerobic composting units until the original substrate was totally replaced and the bioreactor was fed only water and leachate (20% (m/m), removed from the composting units, with a COD ranging between 1 500 and 2 400 $mg.l^{-1}$. At this stage it was not necessary to adjust the pH as the operating pH varied between 7.25 and 7.75.

Experimental Study 1: Digestion of apple pomace using modified composting units on a roller-table

The first study was done on a roller-table to ensure that the pomace and sludge fractions were thoroughly mixed. The study was divided into two phases: A and B, and six 1L-composting units were used for each phase. The substrates for the units were as follow:

Phase A: 6 x 1L modified composting units labelled A2, A5, A10, A15, A20 and A29, as representative of the sampling days, were used. An operational ratio of 2 : 2 : 1 of sludge, pomace and mushroom compost plus 10 ml organic compost activator, were used as composting substrate; and

Phase B: 6 x 1L modified composting units labelled B2, B5, B10, B15, B20 and B29, as representative of the sampling days, were used. An operational ratio of 2 : 12 : 1 of sludge, pomace and mushroom compost plus 10 ml organic compost activator, were used as composting substrate.

The units were incubated at 35°C on the roller-table at 26 rpm. The volume and pH of the leachate, biogas volume and VFA's were determined on days 2, 5, 10, 15, 20 and 29.

Experimental Study 2: Effect of different moisture levels on the digestion process

The purpose of this study was to determine the impact of different moisture levels (30, 40, 50 and 60% (m/m)) on the digestion efficiency. In this study, the juice was pressed per hand from the pomace and the pH of the liquid fraction adjusted to 7.0 with calcium hydroxide ($Ca(OH)_2$). After the juice had been removed, the moisture level of the solid fraction, for the purpose of this study, was taken as zero. The removed liquid fraction was then re-added to the solid fraction so as to attain the required moisture level (Table 1). Anaerobic sludge, collected at the Kraaifontein Municipal Works, was centrifuged for 15 min at 10 000 rpm to concentrate the solids and this was then used as inoculum (10% of the total mass).

The units were then flushed with nitrogen for 1 min, sealed, and incubated at 35°C. Every 24 h, the leachate was collected from each unit and the volume and pH of the leachate and volume biogas were measured. The volume and pH of

the leachate, where necessary, was adjusted and used as substrate for the UASB bioreactor. The removed volume from each unit was replaced with 20 ml bioreactor effluent of which the pH had been adjusted to 10.0 with NaOH. The biogas and VFA's compositions were determined after 5 and 10 days, respectively.

Experimental Study 3: *Affect of adding water, UASB reactor effluent and a water and UASB reactor effluent mixture, on the digestion of apple pomace*

The purpose of this study was to determine what impact the addition of different 'moisturising liquids' such as water, UASB bioreactor effluent and a mixture of water and UASB bioreactor effluent, will have on the anaerobic composting of apple pomace. Anaerobic sludge, obtained from Kraaifontein Municipal Works, was centrifuged and added as inoculum (20% (m/m)). For the purpose of this study, nine composting units were used (Fig. 1). The apple pomace was hand pressed and water was then added, as summarized in Table 2, to obtain moisture levels of 30% (m/m) (Units 1, 2 and 3) and 60% (m/m) (Units 4, 5 and 6). For composting Units 7, 8 and 9, the pomace was further washed per hand under running water so as to investigate the washing effect on the pH (Table 2). By washing the pomace with water, the pH of the pomace increased slightly and it became saturated with water, thus resulting in a higher moisture content (82% (m/m)) at start-up.

Units 1, 4 and 7 received only UASB reactor effluent. A ratio of 1: 1 of reactor effluent to water was added to Units 2, 5 and 8, while only water was added to Units 3, 6 and 9. Moisture (80 ml) was added to each unit everyday for the first 19 days. Urea and phosphate was added to the 'moisturising liquids' at a concentration of 500 $mg.l^{-1}$ and the pH was adjusted to 10. From day 20 onwards, 80 ml of moisture was added every second day. The data showed that the microbial population was well established by this time and that less liquid was needed during the digestion process.

The volume and the pH of the leachate and volume biogas were determined daily and the composition of biogas and VFA's were analysed every fifth and tenth day, respectively.

Table 2. Different 'moisturisers' added to determine the impact on the pH stabilisation and biogas production during the digestion of apple pomace.

Composting unit	Moisture added (80 ml; pH 9.0)	Substrate
		30% moisture
1	Only reactor effluent	
2	1:1 water + reactor effluent	250 g pomace + 110 g water + 72 g sludge
3	Only water	(20% (m/m) inoculum)
		60% moisture
4	Only reactor effluent	
5	1:1 water + reactor effluent	200 g pomace + 300 g water + 100 g sludge
6	Only water	(20% (m/m) inoculum)
		Washed and water saturated (82% moisture)
7	Only reactor effluent	
8	1:1 water + reactor effluent	300 g pomace + 60 g sludge
9	Only water	(20% (m/m) inoculum)

Results and discussion

Experimental Study 1: Digestion of apple pomace using modified composting units on a roller-table

Composting units were used to anaerobically compost apple pomace on a roller-table. Anaerobic sludge, from Kraaifontein Municipal Works at different ratios, was used as inoculum. After the first day, the pomace and sludge mixture were found to form balls in all the composting units, but these disappeared again after about six days. The rolling motion and the fact that the mixture was fairly dry, could be possible explanations for this occurrence. The biogas and leachate volumes produced, as well as the average pH of the leachate, are presented in Table 3.

The digestion process was stopped after 30 d because the production of biogas had ceased and the pH dropped to levels too low for efficient anaerobic digestion (Nel & Britz, 1986). The pH dropped rapidly from 6.10 (Phase A) and 6.17 (Phase B) to 4.80 (Phase A) and 4.18 (Phase B) by day 30. The drop in pH was ascribed to the accumulation of VFA's in the composting units as illustrated in Fig. 2. Initially, the total VFA's (TVFA's) were relatively low (between 125 and 400 $mg.l^{-1}$), but accumulated as the process continued (Fig. 2), with total VFA amounts of around 5 000 $mg.l^{-1}$ measured by day 30 of the process. Acetic acid was produced as the major VFA in all of the units, with butyric and propionic acid being found in lower concentrations (< 300 and < 5 $mg.l^{-1}$, respectively) in some of the units.

The methane content of the biogas of the units in Phase A was overall better than in Phase B. Methane content of the biogas varied from as low as 33% (v/v) at the beginning of the process to 86% (v/v) after 20 d. The methane (%) decreased again to 18% (v/v) near the end of the process, probably as a result of the inhibitory effect of the low pH.

The colour of the digesting mixtures darkened from yellow to dark yellow almost brown. Leachate was first produced after 13 days of digestion. A rough estimate of the digesting volume showed that there was not a significance reduction in volume of the substrate. From the results in Table 3, it is obvious that the composting process in Phase A was more efficient than in Phase B as the units in Phase A produced much more biogas and the average pH was higher than

Table 3. Final efficiency of the composting units in Phases A and B during the digestion of apple pomace on a roller-table at 35°C.

	Digesting Phase A	Digesting Phase B
Average leachate pH	4.58	3.85
Total leachate volume (ml)	71.0	91.0
Total biogas volume (ml)	1 600	1 255

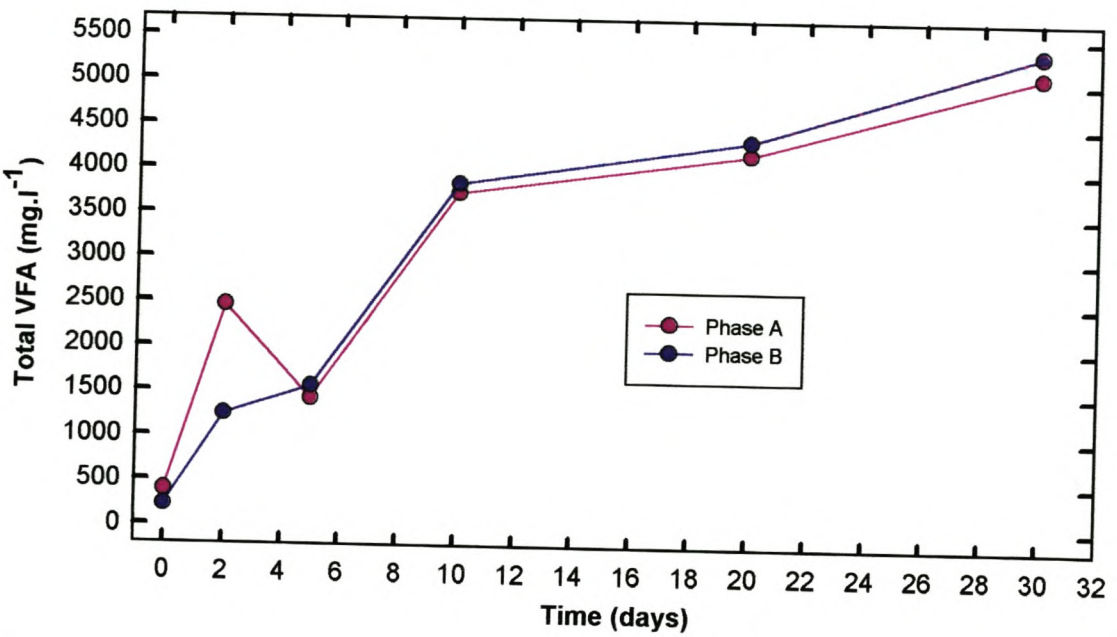

Figure 2. Total VFA's measured during the digestion of apple pomace with a roller-table as mechanical mixing action.

in the case of the Phase B study. There was also less VFA's measured in Phase A. A possible explanation for the better performance in Phase A could be the higher ratio of sludge inoculum to pomace, which could directly be equated to the size of the microbial community.

It was concluded from the data obtained that if the process is to be made more efficient, the leachate would have to be removed to prevent the accumulation of VFA's and thus the dramatic drop in pH, which subsequently lead to microbial growth inhibition and subsequent process failure.

Experimental Study 2: Effect of different moisture levels on the digestion process

Based on the data obtained in Experimental Study 1, it was decided that the leachate produced during the digestion process must be removed to prevent the accumulation of VFA's and subsequent drop in pH. Mechanical mixing of the substrate on a roller-table was also excluded for the purpose of this study so as to determine if the rolling motion had any effect on the digestion process. It was also decided that the moisture levels at the beginning of the composting process were inadequate because the substrate appeared to be very dry and subsequently the digestion process did not proceed as well as was expected. The moisture levels were therefore adjusted by re-adding the apple juice that had been removed during the pressing action. The composting units were thus filled with substrate (420, 360, 300 and 240 g) and the moisture levels adjusted to achieve moisture levels of 30, 40, 50 or 60% (m/m), respectively.

According to the results summarised in Fig. 3 and Table 4, the composting Units with 30% (m/m) and 60% (m/m) moisture were found to perform the best when the biogas produced and average as well as final pH's are taken into consideration. The pH of the leachate from these two Units decreased rapidly over the first 20 d after which it stabilised to a more acceptable value of between 5.4 and 5.3. This pH stabilisation can probably be ascribed to the stabilisation and activity of the microbial community.

The total biogas production was more in the 60%-Unit (778 ml) than in the 30%-Unit (465 ml). Between 20 and 150 ml of biogas were produced and measured daily during the first 5 to 6 d of the process for these two Units. Thereafter biogas production decreased to levels near zero, but after 15 days

larger volumes of biogas were measured again. This irregular production of biogas could be due to the fresh inoculum used at the start-up and then later by the increase in pH to a more favourable level around days 15 - 25. The microbial population in the inoculum responsible for the biogas production and digestion of the substrate was probably the most active at the initial stages of the process. In the case of the 40%-Unit a pH of above 5.0 was never reached. Due to the clogging of the leachate outlet at the bottom of the unit, only small amounts of leachate were produced. Subsequently, a build up of VFA's probably caused the low pH (Fig. 3). The digesting process in this unit was stopped after 20 d as no further biogas was produced and the system was badly clogged-up. The accumulation of VFA's and the low pH of the unit were probably the cause of this failure.

Although large volumes of leachate were removed from the 50%-unit and a good final pH was obtained, no biogas was measured and thus was ascribed to a leakage in the cap.

Acetic and butyric acids were the only VFA's that were produced during the digestion process as set-up in this experimental study. Acetic acid was generally measured in slightly higher concentrations than the butyric acid (Fig. 4).

From the results illustrated in Fig. 3 and 4 and the final data summary in Table 4, the best performance efficiency was obtained with the 60%-composting unit. This unit produced the most biogas and had the highest final average pH. It is unsure why the 30%-unit also performed well and not the units with the higher moisture content (40% and 50% (m/m)). Based on the data obtained, it was also decided that mechanical mixing on a roller-table was not necessary as the units could perform well without mixing of the substrate.

Although good results were obtained with the adjustment of the moisture levels to 30 and 60% (m/m) at start-up, the addition of further moisture during the digestion process appears to be a valuable operational parameter in aiding the composting process. In the next experimental study, this parameter was considered.

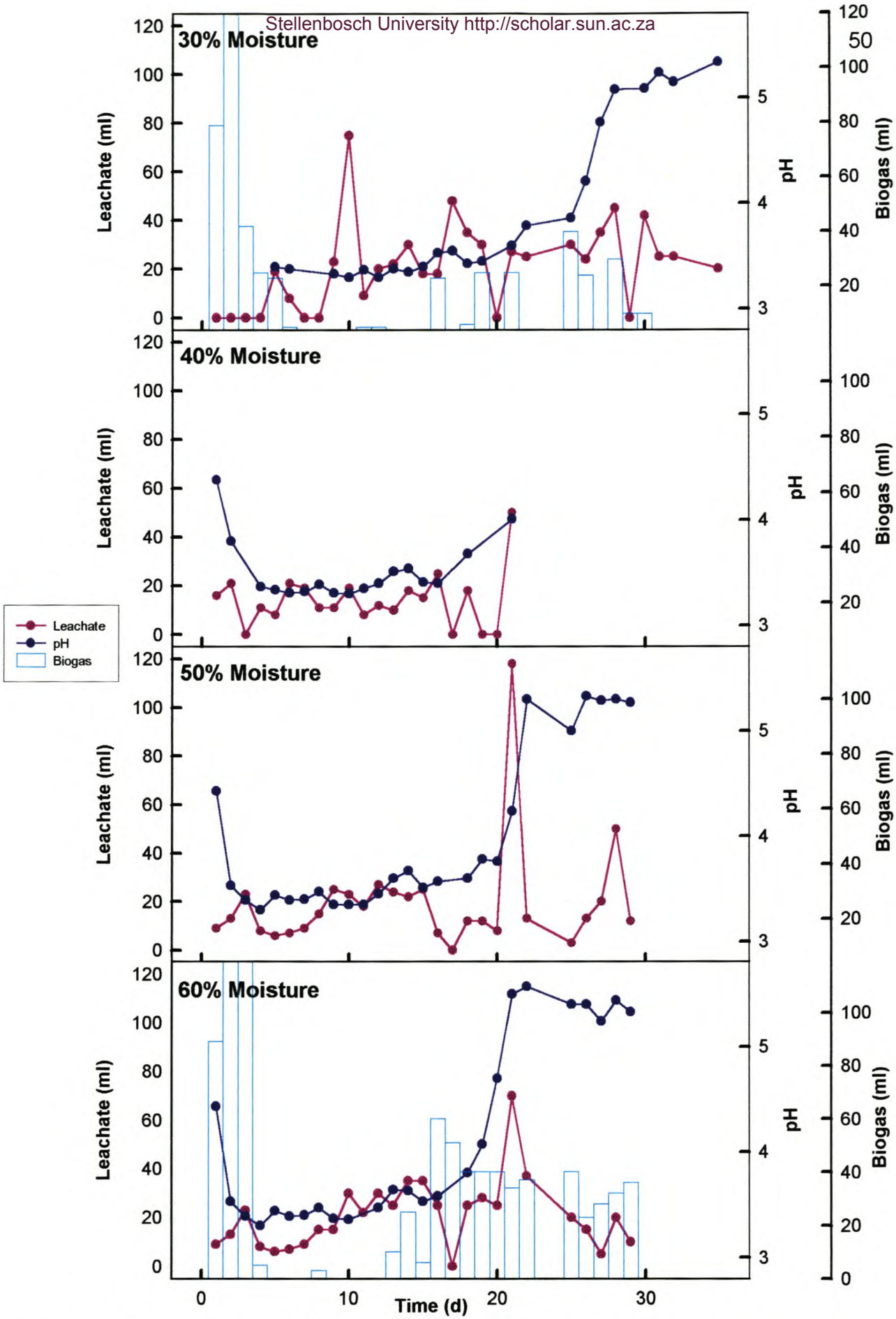

Figure 3. Production of leachate, biogas and leachate pH when apple pomace was anaerobically composted at different moisture levels (30, 40, 50 and 60% (m/m)).

Table 4. Summary of the final performance of the 30, 40, 50 and 60% (m/m) composting units during the digestion of apple pomace.

% Moisture (m/m)	Final pH	Total leachate volume (ml)	Total biogas volume (ml)
30%	5.4	675	465
40%	4.0	334	0
50%	5.3	541	0 (leakage)
60%	5.3	569	778

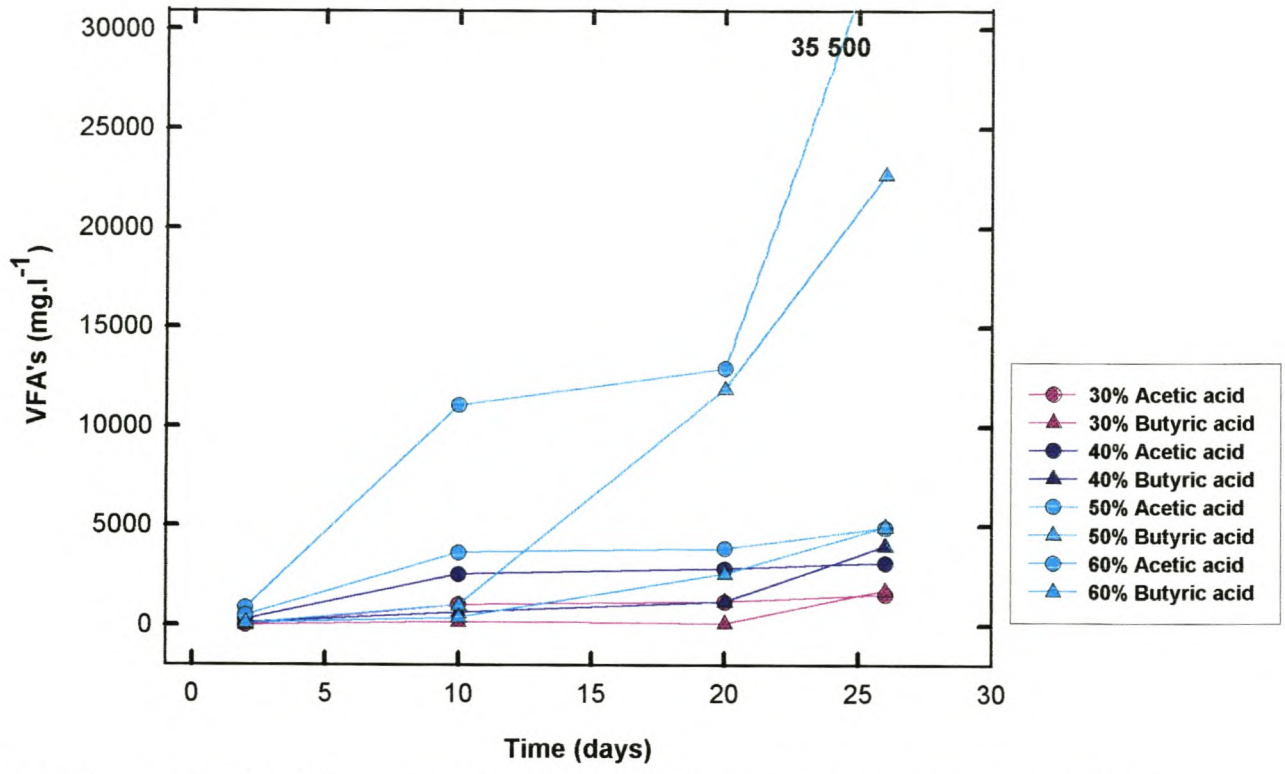

Figure 4. Effect of different moisture concentrations (30, 40, 50 and 60% (m/m)) on volatile fatty acid production during the digestion of apple pomace.

Experimental Study 3: *Affect of adding water, UASB reactor effluent and a water and UASB reactor effluent mixture on the digestion of apple pomace.*

In an attempt to regulate and control the composting process, the emphasis of this study was on pH control through the addition of different 'moisturising liquids' to provide moisture to the digestion process. Three 'moisturising liquids' were selected: water; UASB reactor effluent; and a 1:1 ratio of water and UASB effluent. The liquids were added daily, thus replacing the leachate that was removed. The best two composting units (30 and 60% moisture (m/m)) from the previous study were used as starting points. Apple pomace, thoroughly washed under running water, was also used as a substrate to be composted. The reason for this decision was two-fold: so that the pomace would be saturated with moisture; and to remove part of the fruit solids and carbohydrates with the wash water.

The results for biogas, leachate and VFA's production are presented in Figures 5, 6, 7 and 8. The results will be discussed as three separate phases: Phase 1 (Units 1, 2 and 3, with 30% moisture at start-up), Phase 2 (Units 4, 5 and 6, with 60% moisture at start-up) and Phase 3 (Units 7, 8 and 9, with washed pomace). The most efficient unit of each Phase will be identified based on the results obtained and compared to the other best units in this experimental study.

Phase 1 (Units 1, 2 and 3): During this phase not one of the units reached a pH higher than 5.0 during the digestion process (Fig. 5). The high concentrations of acetic, butyric and propionic acids (>4 000 $mg.l^{-1}$) probably contributed to this (Fig. 6). The best biogas production was achieved in Unit 1, followed by Unit 2 and then Unit 3. The UASB bioreactor effluent used as 'moisturiser liquid' probably provided an additional acidogenic inoculation for the digestion process, thus aiding the production of biogas. Another reason for the high biogas production in Unit 1 could be the good production of acetic acid as shown in Fig. 6. The concentration of acetic acid in Unit 1 was much higher than found for Units 2 and 3 (Fig. 6). In this phase, it was concluded that Unit 1 performed the best, because the biogas production was the highest, a fairly good final pH and an excellent production of VFA's, was achieved.

Phase 2 (Units 4, 5 and 6): In this phase three 'moisturising liquids' were used at a moisture level of 60% (m/m) at start-up. The pH of Unit 5 reached

5.0 and higher by the end of the composting period (Fig. 7). The average concentration of VFA's was on average much lower in these three Units than found for Units 1, 2 and 3 (Fig. 6). This could be due to the fact that the initial moisture content was higher in this study. Composting processes develop best when the composting substrate is wet enough because the microbial community in the substrate needs moisture to obtain maximum activity (Raadt, 2001). The VFA's of Unit 5 were at the lowest concentrations, followed by Unit 4 and then Unit 6.

In total it was concluded that Unit 4 performed the best in this phase. Although the final pH was not as high as for the other two Units, large volumes of biogas were measured and the concentrations VFA decreased fairly well. Again, as found in Phase 1, the addition of bioreactor effluent as 'moisturising liquid', could be responsible as a result of the more favourable conditions for the acidogenic population.

Phase 3 (Units 7, 8 and 9): In this phase, Units 8 and 9 reached pH levels of well above 5.0 (Fig. 8). This was ascribed to the higher moisture level (82% (m/m)) as well as to the large volumes of leachate (between 80 and 125 ml at times) that were removed. Compared to the other units of Phases 1 and 2, the lowest concentrations of VFA (<1 500 $mg.l^{-1}$) were detected in these three units and this probably contributed to the elevated pH levels for all three Units of this Phase (Fig. 6).

The profile for leachate volume removed was found to be very similar for Units 7, 8 and 9 with maximum volumes removed between days 28 and 40. This appeared to have had a very positive effect on the systems, because the increase in pH and decrease in VFA's was observed over this period of time.

Unit 7 was found to produce the largest volumes of biogas, while no biogas was measured for Unit 9 and very little for Unit 8. The absence of biogas from Unit 9 could probably be ascribed to a leakage at the cap or just poor digestion. Unit 7 performed the best regardless of the fact that the final pH was not the highest or above a level of 5.0.

General discussion: On day 43 the composting process was terminated

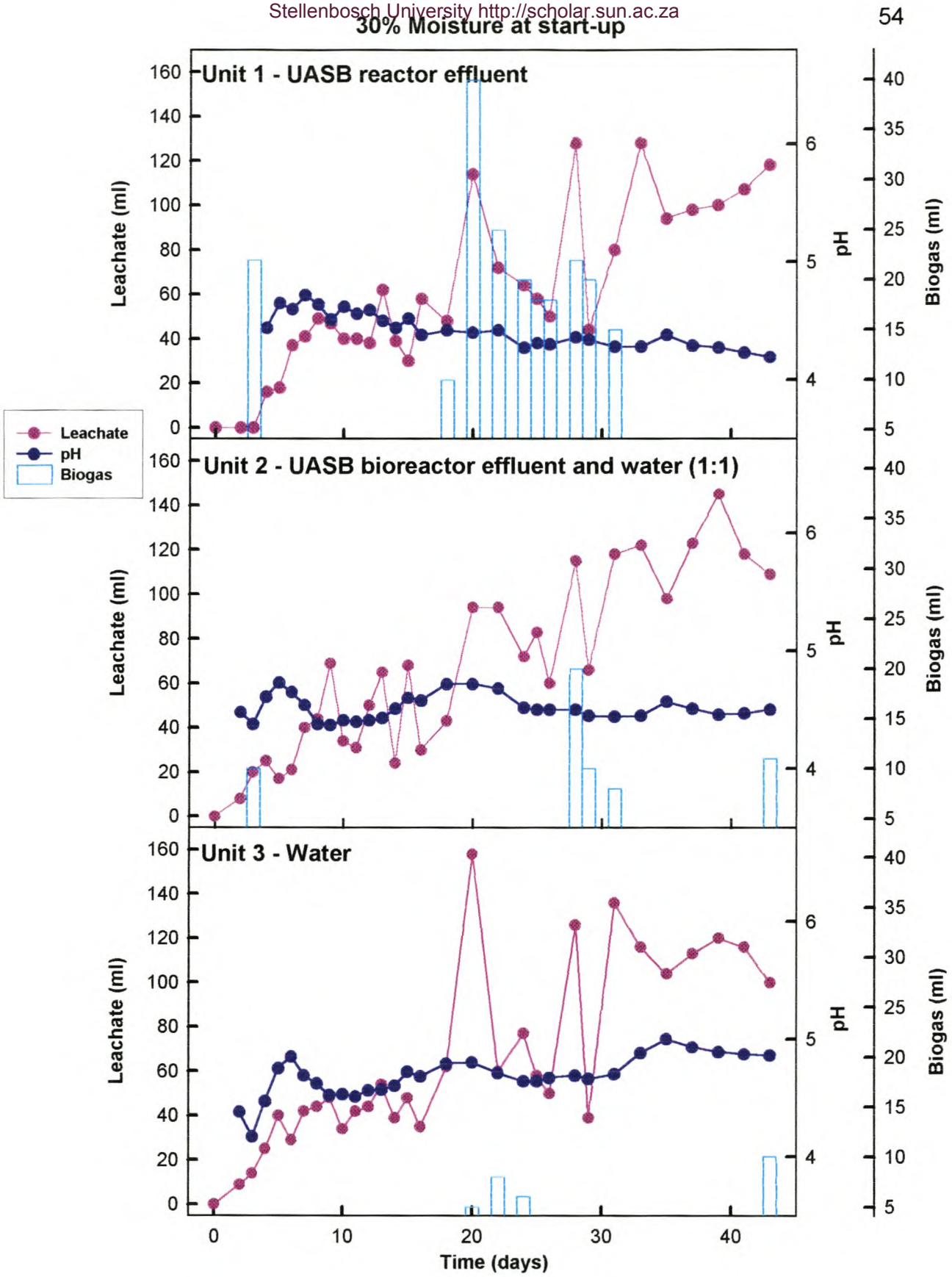

Figure 5. The effect of different 'moisurising liquids' on the production of biogas, volume and pH of leachate, with a 30% moisture level at start-up.

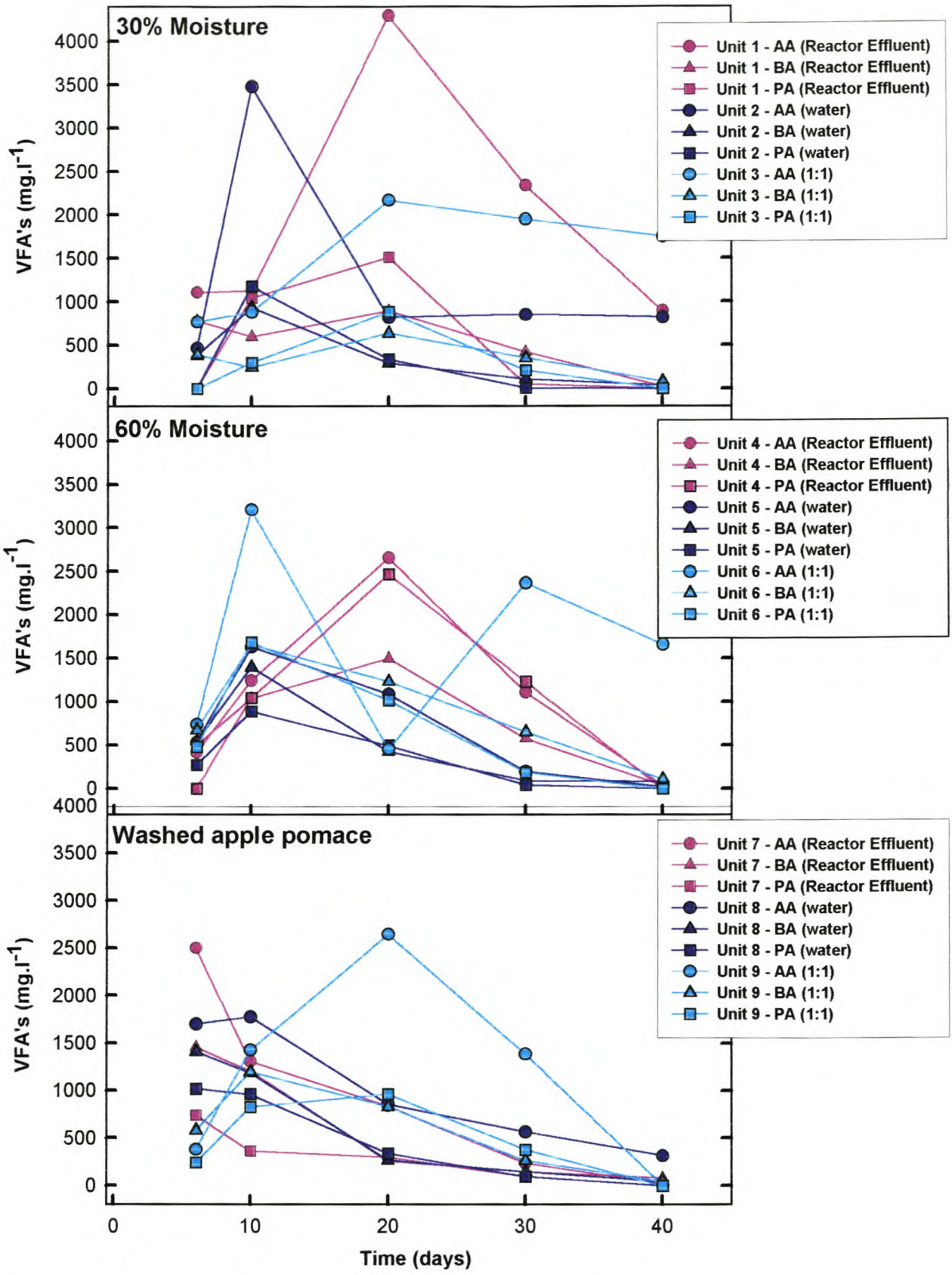

Figure 6. Effect of three different 'moisturising liquids' (water, reactor effluent and 1:1 water and reactor effluent) on the production of acetic acid (AA), butyric acid (BA) and propionic acid (PA) during the digesion of apple pomace.

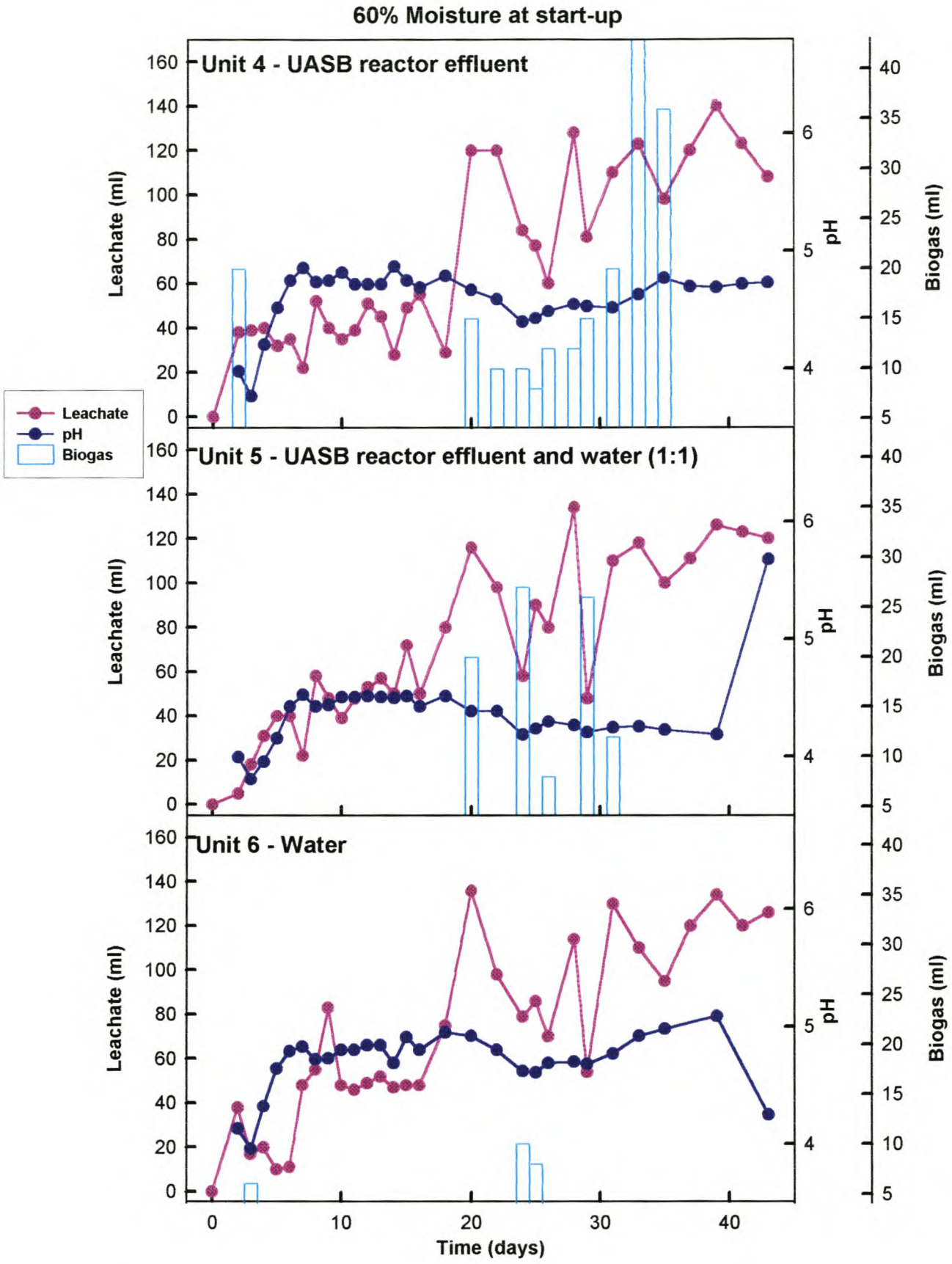

Figure 7. The effect of different 'moisturising liquids' on the production of biogas, volume and pH of leachate, with a 60% moisture level at start-up.

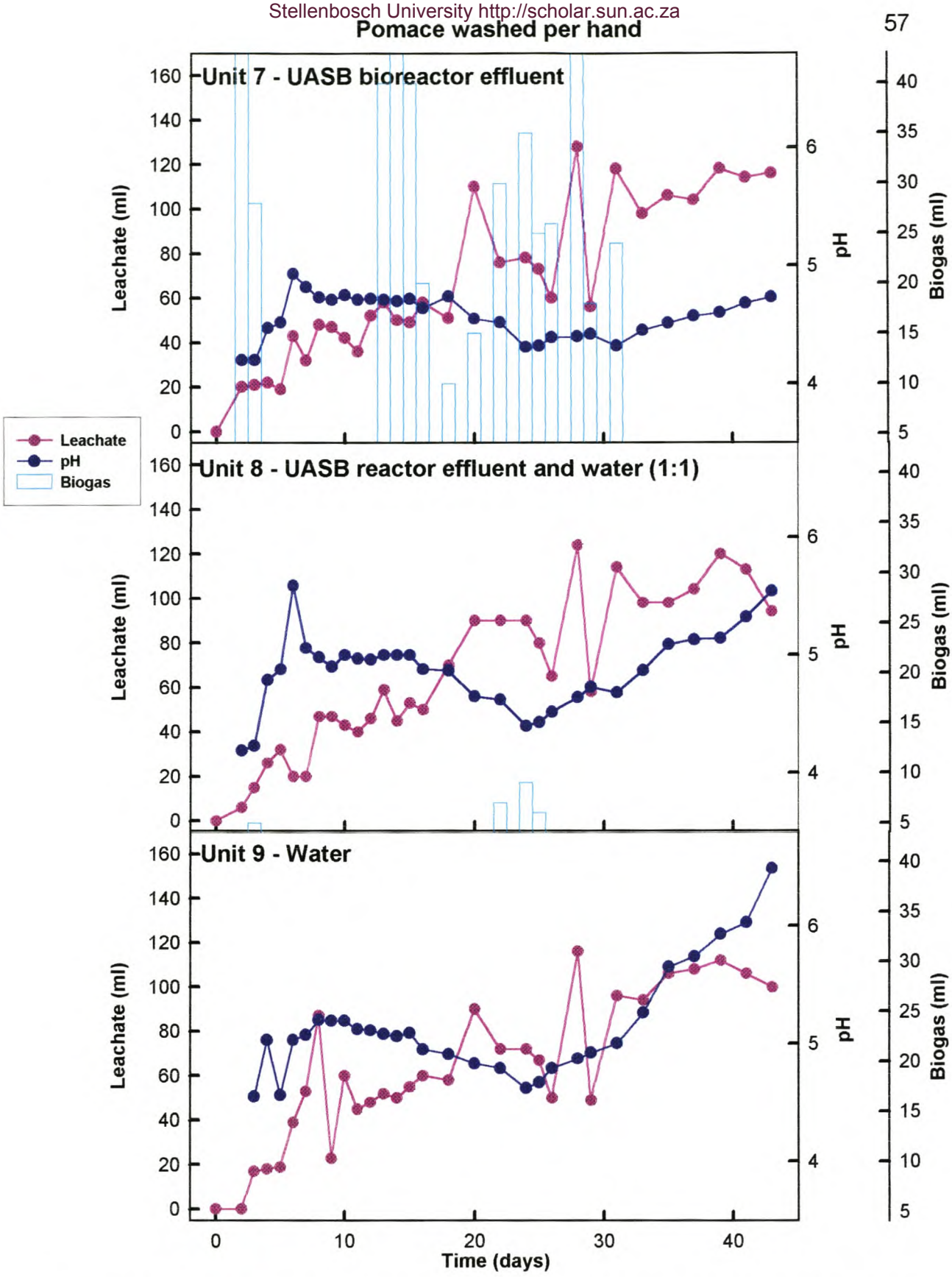

Figure 8. The effect of different 'moisturising liquids' on the production of biogas, volume and pH of leachate, with washed apple pomace at start-up (82% moisture (m/m)).

because the final VFA concentrations had decreased to an acceptable level and the pH of most of the Units had increased to acceptable levels. In addition, the final compost produced in Units 4, 5, 6, 7, 8 and 9 had a healthy looking brown colour, while the compost in Units 1, 2, and 3 was dark green and very moist. Based on the colour of the compost, final pH and the aroma from the compost material, the best results were obtained with composting Units 8 and 9. The final pH of these units was between 5.6 and 6.5 and the compost was not as wet as in the case of the other units. Unit 7, with the UASB bioreactor effluent as 'moisturising liquid', performed the best in this study. This unit produced the most biogas. Although the final pH of this Unit was fairly low, the final concentration of the VFA's was generally the lowest (84 and 20 $mg.l^{-1}$ for acetic and butyric acid, respectively). However, when taking all practical and economical factors into consideration, the best results were obtained with Unit 4.

The general conclusion made from the results obtained in this study is that UASB bioreactor effluent was the most suitable 'moisturising liquid' to use in conjunction with washed pomace as the substrate. The question that needs to be asked is whether it will be possible to use washed pomace when scaling-up? This washing action is time consuming and the production of the additional new waste effluent will economically just not be feasible for an industry to treat. Another problem is the pressing action to separate the solid and liquid fractions of the pomace. This too is very time consuming and will present problems when large scale composting has to be considered. Other alternatives should be investigated to try and minimize the pressing and production of additional waste waters.

Conclusions

In these three experimental studies, several important lessons were learned and the following conclusions can be drawn. For the anaerobic composting of apple pomace, it is not necessary to employ a mechanical mixing action as the process can successfully proceed without any mixing. The strict control of specifically identified operational parameters (pH, inoculum, moisture level, moisture volume, VFA production and VFA removal) during the anaerobic composting process is of great importance when optimisation of the process is to be considered.

Furthermore, the sort of inoculum is important in the digesting process, as it is directly responsible for the microbial community necessary to digest the pomace. From the data obtained in Experimental Study 2, it was concluded that the correct inoculum and thus the most suitable microbial population, is responsible for the production of biogas early in the composting process when the acidogenic bacteria are still dominantly active. It was also concluded that when optimising the anaerobic composting process, the ratio of inoculum to the substrate volume to be composted is of great importance. A too small inoculum will not be active enough to start the digestion process. On the other hand, a too large inoculum will have an important negative economical impact when the process is scaled-up. Large inoculums take up large volumes that displace volumes of waste that can be composted. It is also important to consider the large mass (weight) of the inoculum in terms of the process.

In this study large concentrations of volatile fatty acids were produced during certain of the composting studies and these were found to be the cause of bad digester failures when not removed or neutralised in time. Propionic, butyric and acetic acids were the major acids produced. These acids cause the pH to drop dramatically and sometimes led to situations, which can be referred to as 'sour' fermentation or acidification. Removing the leachate and then using it as a substrate in an UASB bioreactor so as to remove the VFA's before re-adding to the composting units, helped to solve this problem.

Control of the pH was also found to be essential in all the studies conducted and different mechanisms were employed. The first option was to wash the pomace with water, but this is not a very practical method when it comes to scaling-up, as water is scarce and a new polluted effluent is generated. The second option was to press the pomace per hand and to adjust the pH of the liquid fraction before re-adding it to the solid fraction. This too is not very practical when a large volume of fruit wastes needs to be digested. Finally, the possibility of using an UASB bioreactor to recirculate the leachate removed from the composting units was explored. The leachate from the composting units was used as substrate for the UASB bioreactor and the UASB effluent at a more suitable pH of ±6.5 was re-added back into the digestion units to provide the necessary moisture. The UASB bioreactor was thus used to control the pH in the composting

systems by removing the accumulated VFA's. An additional advantage of this option was the continuous addition of fresh and active anaerobic microbes.

Another aspect that was identified as an operational parameter that had to be carefully controlled and optimised was the moisture content. Different 'moisturising liquids' were thus evaluated to provide moisture during the digesting process. The data during these studies showed that UASB bioreactor effluent was the best 'moisturiser' to use. The effluent from the bioreactor is known to be able to serve as an inoculum with the necessary methanogenic bacteria. Thus, by adding it to the composting units as a 'moisturiser', it provided an additional inoculation. This could be a possible explanation for the better results obtained in the studies (Units 1, 4 and 7) where UASB bioreactor effluent was used as 'moisturiser'.

The moisture content (%) in the digestion units was also identified as an important parameter to take into consideration. In the studies it was found that better results were obtained when the moisture content at start-up was higher (60% or higher (m/m)).

It was furthermore concluded that future research must include the scaling-up of the anaerobic composting process as well as the starting-up and maintenance of a larger UASB bioreactor. Solid peach waste (pulp) must also be evaluated as part of the composting substrate. To make the composting process more economically advantageous, the composting period needs to be drastically shortened. Possible ways to accomplish may include the addition of sodium bicarbonate and the use of larger inoculum ratios.

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CHAPTER 4

SCALING-UP AND OPTIMISATION OF AN APPLE POMACE AND PEACH PULP ANAEROBIC COMPOSTING TECHNOLOGY

Abstract

In this experimental study a mixture of apple pomace and peach pulp was anaerobically composted. The objective of the first experimental study was to determine the ratio for the mixture in the composting substrate. After this was defined, different inoculums were used to study the affect on the composting process. After a suitable composting substrate was established, the experiment progressed to the next stage, which was the scaling-up of the composting process. To achieve this, large composting units were built to fit the requirements of the study. The digestion process was improved by using cattle manure as an inoculum as well as sodium bicarbonate to aid the process and kept it from dropping to a pH that was not suitable for anaerobic composting. In the end, a method to produce stable compost that more or less met the same requirements as aerobic compost was developed with the added advantage of methane production.

Introduction

The disposal of solid fruit wastes in South Africa was in the past not considered a serious problem. However, since the implementation of the new Water Act and Environmental Law of 1998 and 2000, respectively, regulations have become much more strict (Anon., 1998; Glazewksi, 2000). This was confirmed after discussing the situation with production managers at fruit processing plants, when it became obvious that the fruit processing industry has grown too large to just regard the disposal of solid wastes as an insignificant problem (Van Zyl, 2001). To make matters worse, many plants are faced with the problem of diminishing landfill sites and the increasingly high costs of transportation of the solid waste to distant landfills (Du Toit, 2001). The use of charcoal or electricity to heat up boilers, pasteurisers and washing water has also become very expensive (Van Niekerk, 2001).

Anaerobic composting is a relatively new technology that has received a lot of research attention during the past few years. The basic principle of the anaerobic composting technology is composting of solid wastes in the absence of molecular oxygen and this presents a combined advantage of the production of biogas, which can be recycled as heat energy, as well as compost, which in turn can be used as a value-added soil fertiliser (Lomas *et al.,* 2000).

In Chapter 3 of this thesis, a 2-litre method was developed to anaerobically compost apple pomace. The aim of this study was to scale-up this developed anaerobic composting technology to at least 20 L and to broaden the solid waste fraction to include peach pulp as part of the composting substrate. The use of anaerobic sludge (Kraaifontein Municipal Works), anaerobic compost and cattle manure as inocula was also re-evaluated in the larger scale units.

Material and methods

Small anaerobic composting units

In this study, modified 2 L glass containers, as described in Chapter 3 of this thesis, were used as composting units (Fig. 1). A layer of glass wool (Lasec, Cape Town) was placed in the bottom of each unit to serve as a filter to prevent the fruit solid waste from clogging the leachate outlet. Moisture was added through the cap opening. Biogas exited via a glass extension on the upper side, while the leachate was removed through a glass extension at the bottom of the unit. A third glass extension was used to flush the system with nitrogen. The compost units were incubated at 35°C at all times in a temperature-controlled room.

Larger anaerobic composting units

Anaerobic composting units with a total container capacity of 20 L, as illustrated in Fig. 2, were designed and constructed from PVC. The units were large enough to allow the composting of between 15 and 17 kg of fruit solid waste. The final PVC container was 500 mm in height and had a diameter of 400 mm. Rubber rings were fitted between the unit and the lid before the lid was bolted down with 18 bolts to ensure a gas tight seal. Fittings were positioned in the centre of the lid, in the bottom of the unit and on the side. These were used as

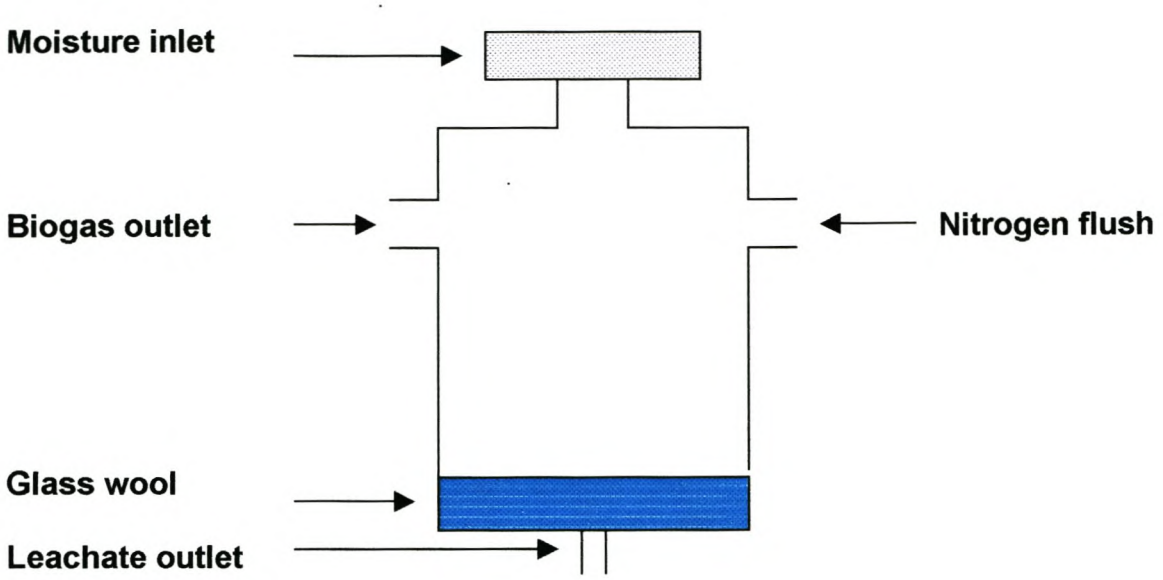

Figure 1. Modified 2 L glass container used as anaerobic composting unit for the digestion of fruit solid waste.

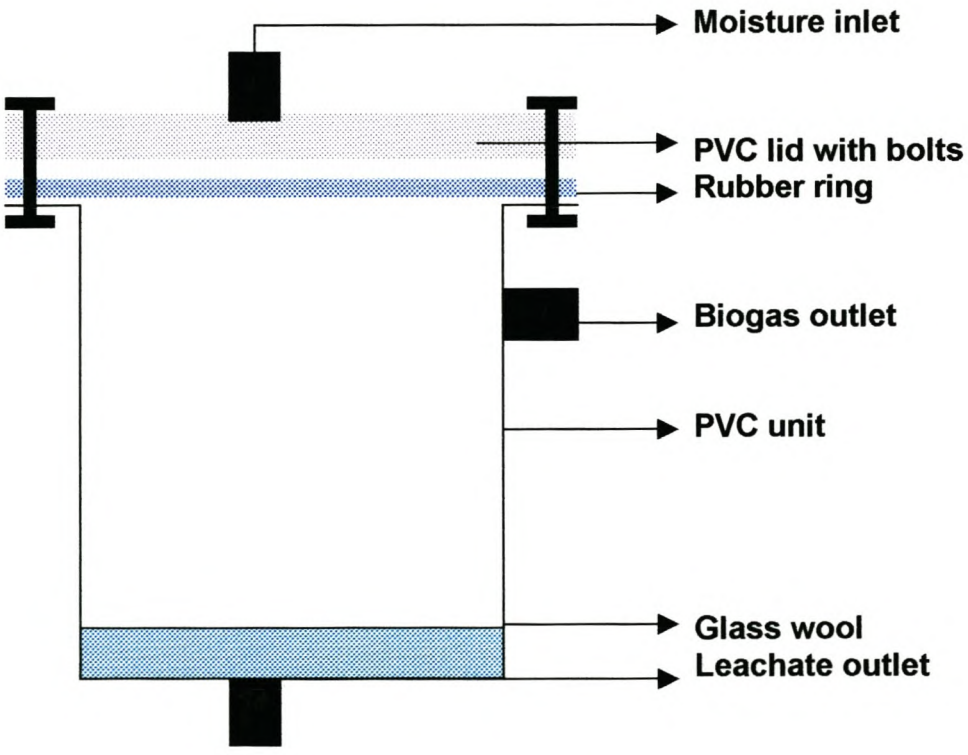

Figure 2. Large 20 L PVC units for the digestion of fruit solid waste.

either inlets or outlets for the biogas and leachate removal, as well as for the addition of UASB bioreactor effluent (Fig. 2).

Substrate, growth factor extract and inocula

Apple pomace was obtained from Appletiser, Grabouw, for the purpose of this study. The pomace was frozen in plastic bags and stored at –18°C. It was defrosted overnight when needed and used in the same form as when it was collected, thus without any pressing or washing actions.

Sludge was collected from the Kraaifontein Municipal Works and stored at 4°C.

The anaerobic compost, which was used as an inoculum in most of the studies, was the anaerobic compost fraction that was formed as final product during previous studies performed in Chapter 3 of this thesis.

Cattle manure extract (CME) was used as a growth factor stimulant and was prepared by boiling 250 g cattle manure in 1 L water for 30 min. The mixture was filtered before use.

Analytical methods

The following parameters were monitored according to Standard Methods (APHA, 1992): pH and Chemical Oxygen Demand (COD). Volatile fatty acid (VFA) concentrations were analysed using a Varian (Model 3700) gas chromatograph equipped with a flame ionisation detector and a 30 m Fused Silica capillary column with a 007 bonded FFAP stationary phase (Quadex Co., New Haven). The column temperature was started at 105°C for 2 min and then increased to 190°C. The total running time was 25 min. The detector and inlet temperatures were set at 300°C and 130°C, respectively. Nitrogen gas was used as the carrier gas (flow rate: 6.1 $ml.min^{-1}$).

The biogas composition was determined using a Varian (Model 3700) gas chromatograph equipped with a thermal conductivity detector and a 2.0 m x 2.0 mm i.d. column packed with Hayesep Q (Supelco, Bellefonte, PA), 80/100 mesh. The oven temperature was set at 45°C and helium was used as the carrier gas (flow rate: 40.0 $ml.min^{-1}$).

UASB Bioreactor

In this study, a laboratory-scale upflow anaerobic sludge blanket (UASB) bioreactor with an operational volume of 2.3 L, was used. The design combined an UASB system with an open gas/solids separator at the top of the bioreactor (Fig. 3) (Trnovec & Britz, 1998).

The biogas exited the system via the top, while the substrate was introduced at the bottom of the bioreactor. The overflow was drained through a U-shaped tube to prevent any atmospheric oxygen from entering the system. The temperature of the bioreactor was maintained at 35°C by using a heating tape that was wrapped round the reactor and this was then connected to an electronic control unit (Meyer *et al.*, 1983). The volume of the biogas produced was monitored using a manometric unit equipped with an electronic controlled counter and a gas-tight valve. The substrate was fed semi-continuously by means of a peristaltic pump, which was connected to an electronic timer. The reactor was seeded with 700 ml granules obtained from a full-scale UASB bioreactor treating brewery effluent.

The granules were activated by circulating an urea and K_2HPO_4 (500 $mg.l^{-1}$ each) mixture through the reactor for 72 h. After that the bioreactor was fed with a solution of 10 $g.l^{-1}$ sodium lactate, 500 $mg.l^{-1}$ K_2HPO_4, 500 $mg.l^{-1}$ urea, 1 $g.l^{-1}$ glucose, 20 $g.l^{-1}$ yeast extract and 1 $ml.l^{-1}$ trace element solution (Britz *et al.*, 2000; Trnovec & Britz, 1998). The pH was adjusted to 7.5 and the hydraulic retention time (HRT) was set at 24 h and then steadily decreased to 18 h. The substrate was then systematically replaced with leachate removed from the anaerobic composting units until the original substrate was totally replaced and the bioreactor was fed only water and leachate (20% (m/m)) removed from the composting units, with a COD ranging between 1 500 and 2 400 $mg.l^{-1}$. At this stage it was not necessary to adjust the pH as the operating pH varied between 7.25 and 7.75.

Experimental Study 1: Anaerobic composting of a mixture of apple pomace and peach pulp using different inoculums

The aim of this study was to determine if a mixture of apple pomace and peach pulp could be anaerobically composted together. Modified 2 L glass

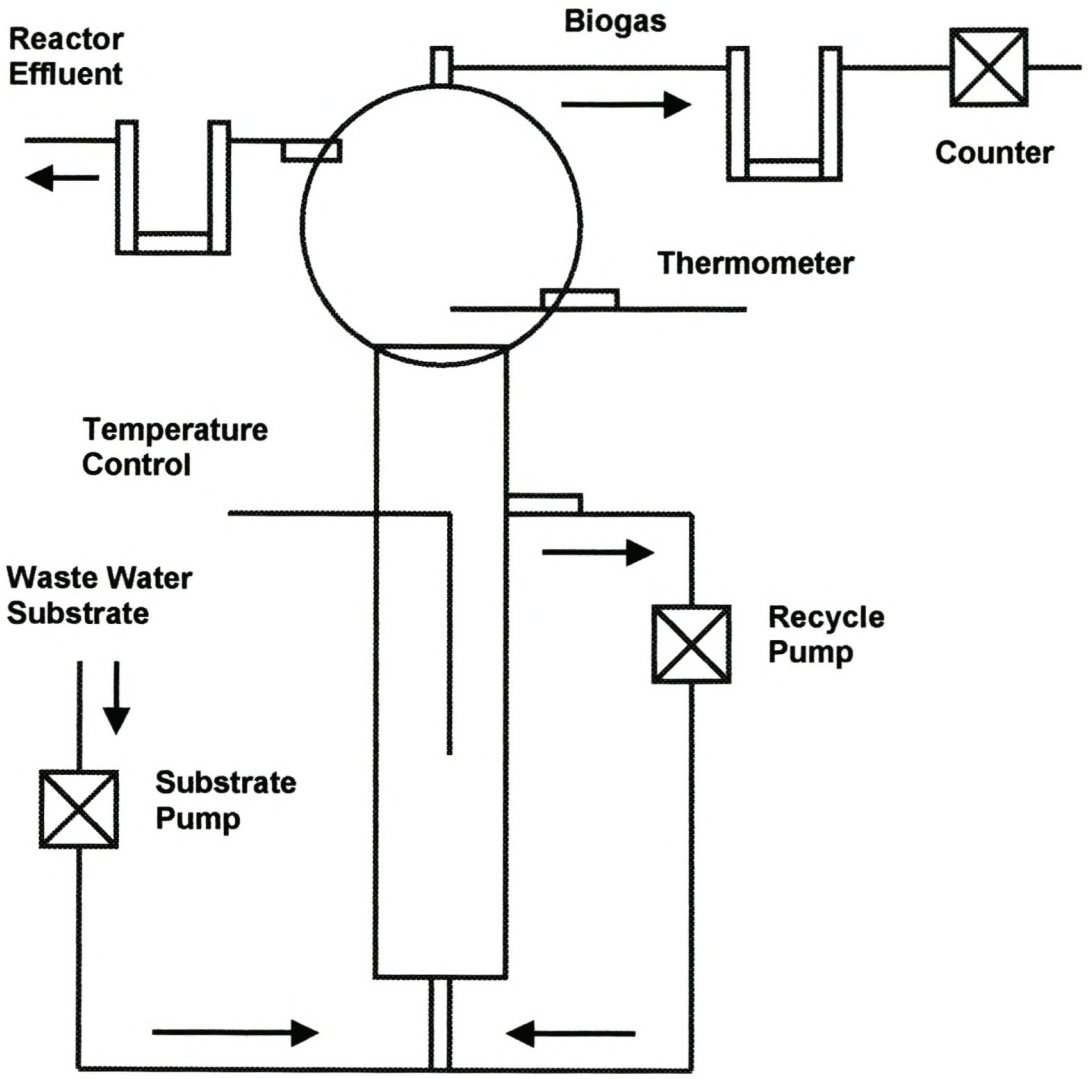

Figure 3. Laboratory-scale upflow anaerobic sludge blanket bioreactor.

containers (Fig. 1) were used as composting units and the effect of three different inoculums (brewery granules, anaerobic sludge and anaerobic compost) were evaluated. The reason for the use of these three inoculums was that the composting substrate differed from the substrate used in Chapter 3 and it was not certain which inoculum would be the most effective for use in this larger scale study.

The substrate used in this study was made up of 10% (m/m) water, 20% (m/m) inoculum, 30% (m/m) apple pomace and 40% (m/m) peach pulp. The total mass of the substrate to be composted was 550 g. Three composting units were used. Brewery granules were added as inoculum to Unit 1, while anaerobic sludge and anaerobic compost were used in Units 2 and 3, respectively. The units were sealed and incubated at 35°C. The leachate was removed from the composting units after every 48 h and replaced with 150 ml UASB bioreactor effluent (RE). The pH of the bioreactor effluent was adjusted to 10.0 by adding sodium hydroxide (NaOH) to the effluent before re-adding it to the units. The biogas produced in the units was measured and the composition analysed and the volume and pH of the leachate produced were determined every 48 h. The COD and VFA's were determined and analysed once a week.

Experimental Study 2: Scaling-up the anaerobic composting process to 20 L composting units

To facilitate the discussion section, the experimental set-up for the following experimental studies (2 – 5) is enclosed (Fig.4) as a flow-diagram.

Based on the data obtained in Experimental Study 1, the first aim of this study was to use larger composting units (20 L), as illustrated in Fig. 5, to determine if the method of anaerobic composting that was developed could be scaled-up. The second aim was to confirm whether anaerobic compost was a better inoculum than brewery granules or anaerobic sludge when doing the evaluation on larger scale.

This study was performed in two phases. During Phase 1, three composting units were used. Each unit was inoculated with a different inoculum (anaerobic compost, anaerobic sludge and brewery granules), which compiled 20% (m/m) of the composting substrate. Results obtained from Phase 1 indicated that anaerobic compost was the best inoculum to use. A second phase (Phase 2)

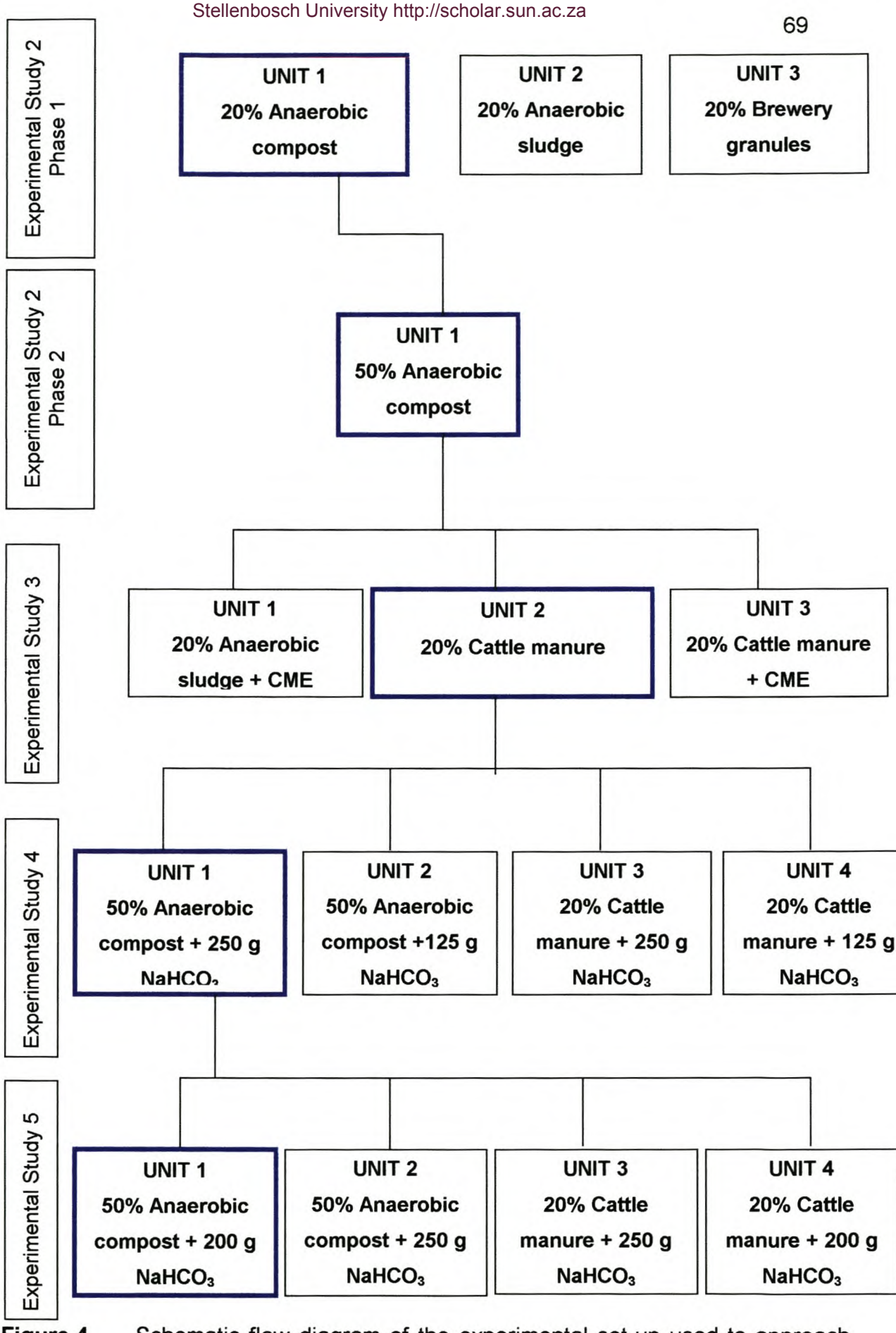

Figure 4. Schematic flow diagram of the experimental set-up used to approach Studies 2 to 5. The blue outline indicates the best unit in each Study (CME – cattle manure extract).

Figure 5. Composting substrate in a 20 L PVC unit at the start of the composting process.

was thus set-up to determine whether a larger inoculum size would have a more positive effect on the composting process. During Phase 2 only one unit was used. This unit (Unit 1) was inoculated with 50% (m/m) anaerobic compost compared to the 20% inoculum used in Phase 1.

The substrate used in Phase 1 was made up of 10% (m/m) water, 20% (m/m) inoculum, 30% (m/m) apple pomace and 40% (m/m) peach pulp (Fig. 5). The total mass of the substrate was 15 kg. Anaerobic compost was added as inoculum to Unit 1, while anaerobic sludge and brewery granules were used in Units 2 and 3, respectively. Unit 1 of Phase 2 was filled with 50% (m/m) anaerobic compost as well as 25% (m/m) peach pulp, 20% (m/m) apple pomace and 5% (m/m) water. The units were sealed and incubated at 35°C. After every 48 h, the leachate was removed from the composting units and replaced with 3 L 'moisturising liquid' (UASB bioreactor effluent (RE) diluted with 50% water). The pH of the bioreactor effluent was adjusted to 10.0 with NaOH before re-adding to the units. The composting process was terminated after a stabile operational pH of > 6.0 was achieved.

Experimental Study 3: *Evaluation of the efficiency of different inoculum sources and a growth factor stimulant on the composting process*

After Experimental Study 2 was completed and since it is possible that anaerobic compost will not always be available, it was decided to use cattle manure and anaerobic sludge as inoculums together with cattle manure extract (CME) as a growth factor stimulant, so as to achieve faster stabilisation results, which ideally should include a faster pH stabilisation.

The aim of this study was thus firstly to determine the efficiency of cattle manure as an inoculum so as to try to achieve a more rapid pH stabilisation and secondly to determine the effect of cattle manure extract, as a growth factor stimulant, on the composting process.

Three composting units were used with a 20% (m/m) inocula of anaerobic sludge in Unit 1 and cattle manure in Units 2 and 3. The substrates for Units 1, 2 and 3 were made up of 20% (m/m) inoculum, 10% (m/m) water, 30% (m/m) apple pomace and 40% (m/m) peach pulp. 'Moisturising liquid' (3 L UASB bioreactor effluent diluted with 50% (v/v) water)) was added to Unit 2, and 3 L (2.5 L of UASB

bioreactor effluent diluted with 50% (v/v) water and additionally 500 ml CME) 'moisturising liquid' were added to Units 1 and 3 every 48 h. The units were incubated at 35°C.

Experimental Study 4: Evaluating the efficiency of the composting process when 125 g and 250 g $NaHCO_3$ was added as pH stabilisers

The aim of this study was to determine if added $NaHCO_3$ would have a pH stabilisation effect on the composting process. Although in a previous study, the best results were obtained when 50% (m/m) anaerobic compost was used as inoculum, it was decided to include 20% (m/m) cattle manure as inoculum as well.

The efficiency of the Units was compared with additions of 250 and 125 g $NaHCO_3$ to the substrates. Units 1 and 2 were filled with 50% (m/m) anaerobic compost (inoculum), 25% (m/m) peach pulp, 20% (m/m) apple pomace and 5% (m/m) water. An addition of 250 g $NaHCO_3$ was made to Unit 1 and 125 g $NaHCO_3$ to Unit 2. Units 3 and 4 were filled with 20% (m/m) cattle manure (inoculum), 40% (m/m) peach pulp, 30% (m/m) apple pomace and 10% (m/m) water. Additions of 250 g $NaHCO_3$ were made to Unit 3 and 125 g $NaHCO_3$ to Unit 4. The units were incubated at 35°C and analyses were performed as discussed previously in this Chapter.

Experimental Study 5: Optimising the $NaHCO_3$ addition

The aim of this study was to optimise the $NaHCO_3$ addition to the composting units to reduce the neutralising costs of the anaerobic composting of apple pomace and peach pulp. The tests were done in duplicate.

In this Study, additions of 250 g and 200g of $NaHCO_3$ were compared. The two inoculums used were 50% (m/m) anaerobic compost and 20% (m/m) cattle manure as the best results were obtained during previous studies where these inocula had been used (Fig. 4).

Units 1 and 2 consisted of 50% (m/m) anaerobic compost (inoculum), 25% (m/m) peach pulp, 20% (m/m) apple pomace and 5% (m/m) water. The only difference between the Units was that 200 g $NaHCO_3$ was added to Unit 1 and 250 g to Unit 2. Units 3 and 4 consisted of 20% (m/m) cattle manure (inoculum), 40%

(m/m) peach pulp, 30% (m/m) apple pomace and 10% (m/m) water. Unit 3 was provided with 250 g $NaHCO_3$ and Unit 4 with 200 g of $NaHCO_3$.

The units were incubated at 35°C. Analyses were performed as previously described.

Results and discussion

Experimental Study 1: Anaerobic composting of a mixture of apple pomace and peach pulp using different inoculums

Peach pulp and apple pomace were digested in 2 L modified containers. The effect of different inoculums (UASB granules, anaerobic sludge and anaerobic compost) on the digesting process, was determined. The results obtained are illustrated in Fig. 6.

The leachate volumes produced during the digestion process (Fig. 6), were very similar for all three the units. Initially, only small volumes of leachate were produced, but these gradually increased and the volume appeared to stabilise at the end of the process, but this will have to be confirmed in future over a longer composting period.

Biogas (Fig. 6) was produced by all three units and the most biogas was measured in Unit 3 where anaerobic compost had been used as inoculum. The CH_4 content for Unit 1 was measured at 37% (v/v) at day 5 and was found to increase to 78% (v/v) by day 15 and then decreased again to 26% (v/v) near the end of the process. The same trend was observed for Units 2 and 3 where by day 5 the CH_4 content was found to be 64 and 60% (v/v), increased to 80 and 86% (v/v) by day 15, but decreased again to 23 and 52% (v/v) by the end of the process.

The pH profiles (Fig. 6) were very similar for all three units. The pH was very low at the beginning of the digestion process (± 3.5), but increased steadily and reached an excellent final pH level of more than 7.0.

The COD levels of the leachate were initially very high for all four of the units (17 000 – 21 000 $mg.l^{-1}$), but then decreased steadily to between 7 000 and 11 000 $mg.l^{-1}$ by the end of the process. Throughout the composting period, Unit 3 had the lowest leachate COD level and a final COD level of 7 000 $mg.l^{-1}$ was achieved.

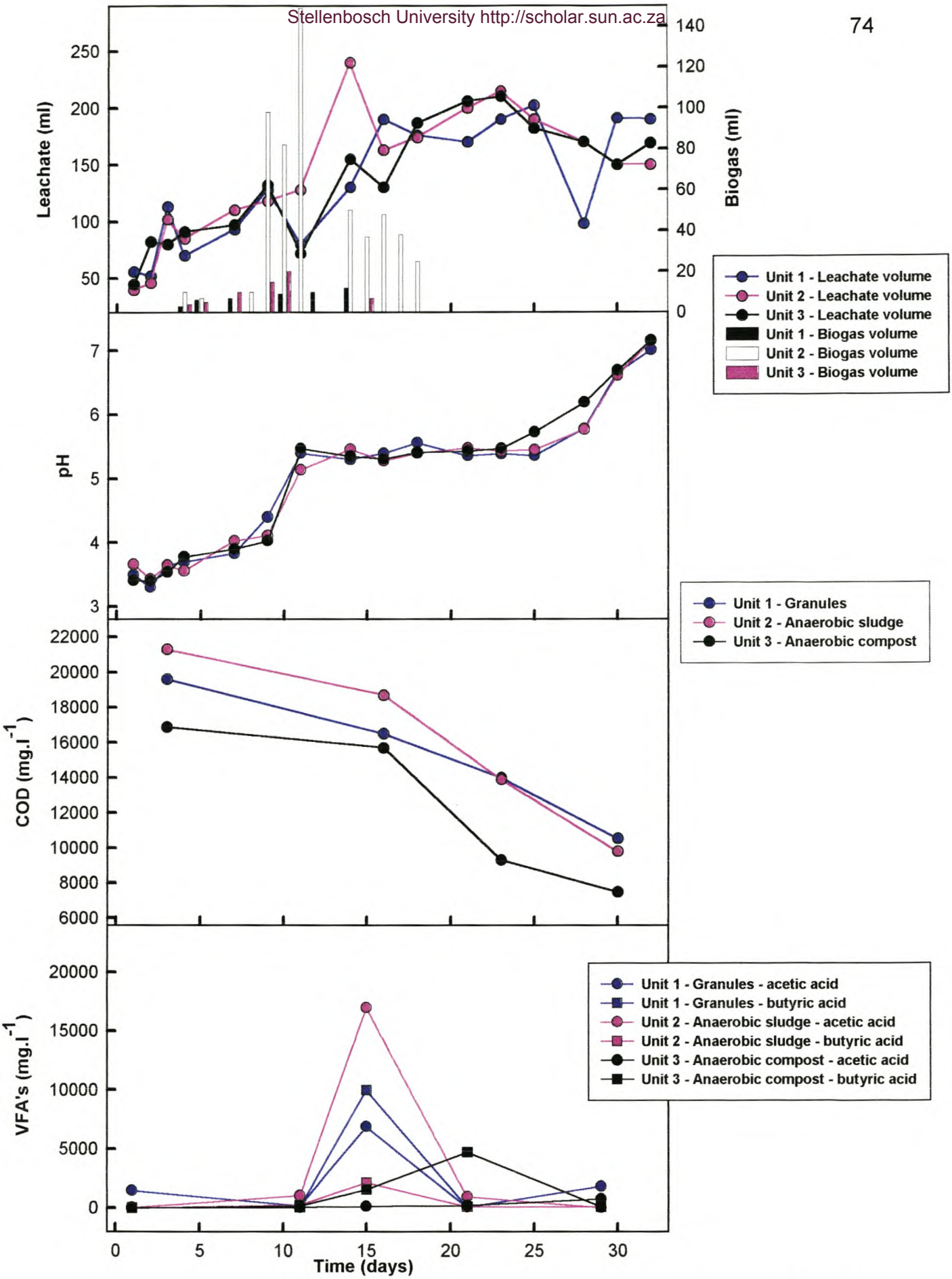

Figure 6. Results obtained during the anaerobic composting of apple pomace and peach pulp in 2 L modified glass containers using different inoculums.

Acetic acid and butyric acid were the only VFA's (Fig. 6) that were detected in larger quantities (levels as high as 17 800 $mg.l^{-1}$ were measured), with lower levels of propionic and valeric acids present in the leachate removed from the units. The highest concentration VFA's were measured in Unit 2, with Unit 1 a little less and the lowest levels of VFA's in Unit 3. The overall profiles of the VFA's concentrations in the leachate suggested an increase to a point as a result of an increased microbial activity and then a sudden decrease by the end of the process. The decrease in VFA's content in the leachate could also be explained by the removal of the leachate from the units. Unit 3, which had been inoculated with anaerobic compost, continuously showed the lowest concentration of VFA's.

When taking the COD and VFA concentrations in the leachate, as well as the production of biogas and the CH_4 content of the biogas into consideration, the best results were obtained in Unit 3. The average leachate pH measured, was also the highest for Unit 3. It appears that anaerobic compost was the best inoculum to use in the subsequent anaerobic composting of apple pomace and peach pulp. This could be due to the fact that the anaerobic compost already contained the optimum balance of the special consortium of micro-organisms that was necessary for the successful composting process. Although good results were obtained during this study, the period of composting was still too long (34 days), and thus is important especially when the economical aspects of the process are taken into consideration.

Experimental Study 2: *Scaling-up the anaerobic composting process to 20 L composting units*

Larger PVC composting units (20 L) were used to determine if the anaerobic composting method that was developed is suitable for scaling-up. This study was performed in two Phases. In Phase 1, anaerobic sludge and brewery granules (Units 2 and 3) as inoculum sources were compared to anaerobic compost (Unit 1) to find the most suitable inoculum that would facilitate the composting process over a period of 28 d. In Phase 2, a 50% (m/m) anaerobic compost inoculum was used and the results were compared to the results obtained from Phase 1. The results obtained are presented in Fig. 7, 8 and 9.

Phase 1: A pH of >6.0 was reached after 11 d in Unit 1 (Fig. 7). Although the pH dropped after 13 d, it increased again after day 17 to a final

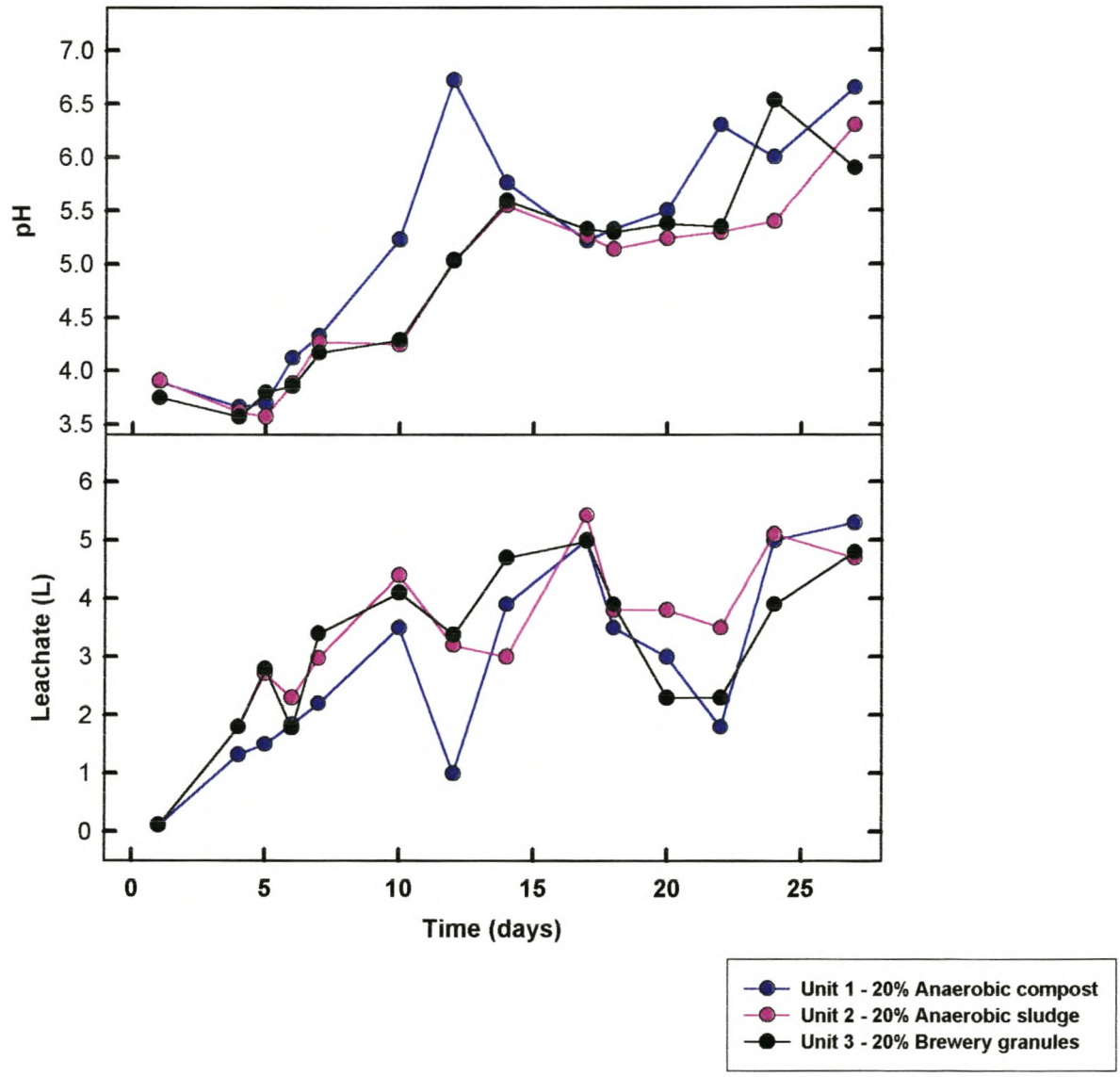

Figure 7. Volume leachate produced and pH of leachate when 20% (m/m) each of anaerobic compost, anaerobic sludge and brewery granules were used as inoculums.

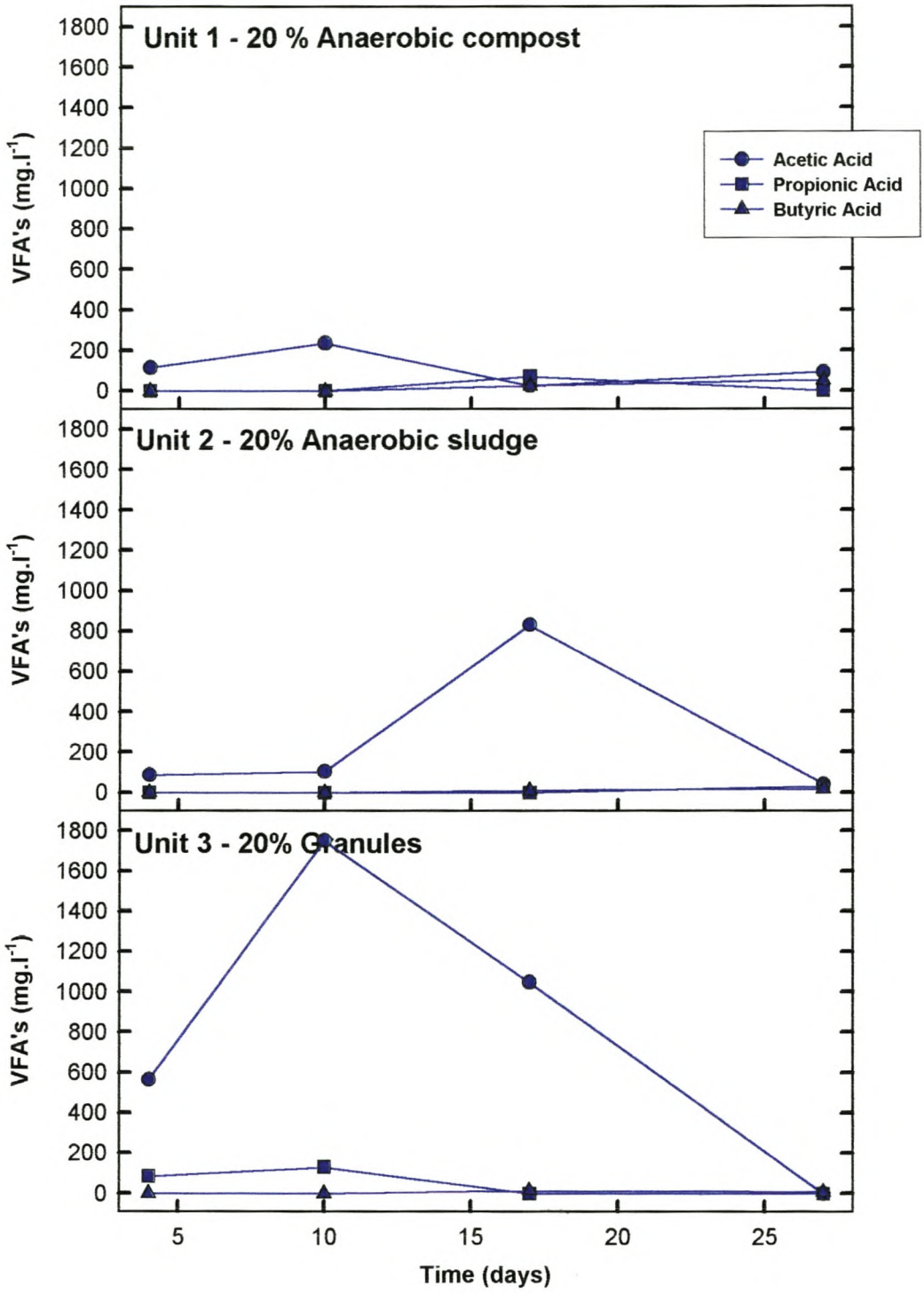

Figure 8. Accumulation of the VFA's (acetic, propionic and butyric acid) during the composting of apple pomace and peach pulp when anaerobic compost, anaerobic sludge and brewery granules were used as inoculums.

pH of >6.5. The pH profiles for Units 2 and 3 were very similar with end pH values around pH 6.0, but differed from Unit 1 in that the pH increased at slower rates. These final pH values are in the range that has been recommended for successful composting (Minaar, 2001).

A total volume of 3 L 'moisturising liquid' (UASB-RE and water) was added to the units every 48 h and thus the removal of more than 3 L leachate volumes was considered as an indication of a stabile system (Fig. 7). After 7 days all the units produced more than 3 L leachate. Although this was not maintained throughout the composting period, the general tendency was that more leachate was produced nearing the end of the composting process suggesting a strong mass reduction. By removing the leachate, VFA's were also removed and the VFA profiles reflected this tendency. After 17 days the VFA concentrations started to decrease (Fig. 8).

The production of VFA's in Unit 1 was very low compared to Unit 2 and especially Unit 3 (Fig. 8). The low concentration of VFA's in Unit 1 could be a possible explanation for the higher pH values measured during the digesting process. Another explanation could be that the anaerobic compost which was used as inoculum, contributed to larger concentrations of acid utilising micro-organisms in Unit 1 than was present in the other units. Acetic, propionic and butyric acids were the VFA's produced in the largest quantities. Valeric acid was also measured, but only in small concentrations (2 – 16 $mg.l^{-1}$). The profiles of acetic acid exhibited an increase followed by a decrease in concentrations. This could possibly be an indication that the micro-organisms were most active during this stage of the process. Acidogenic micro-organisms present in anaerobic processes use a specific metabolic pathways under normal conditions during which acetic acid is produced as the key metabolite for use by the methanogens (Atlas, 1997).

Phase 2: Based on the data obtained in Phase 1 of this Study, it was decided to use a larger inoculum size so as to achieve better composting results. A second phase (Phase 2) was performed to determine whether a larger inoculum size would have a more positive effect on the composting process and to determine how well a 50% (m/m) anaerobic compost inoculum would perform

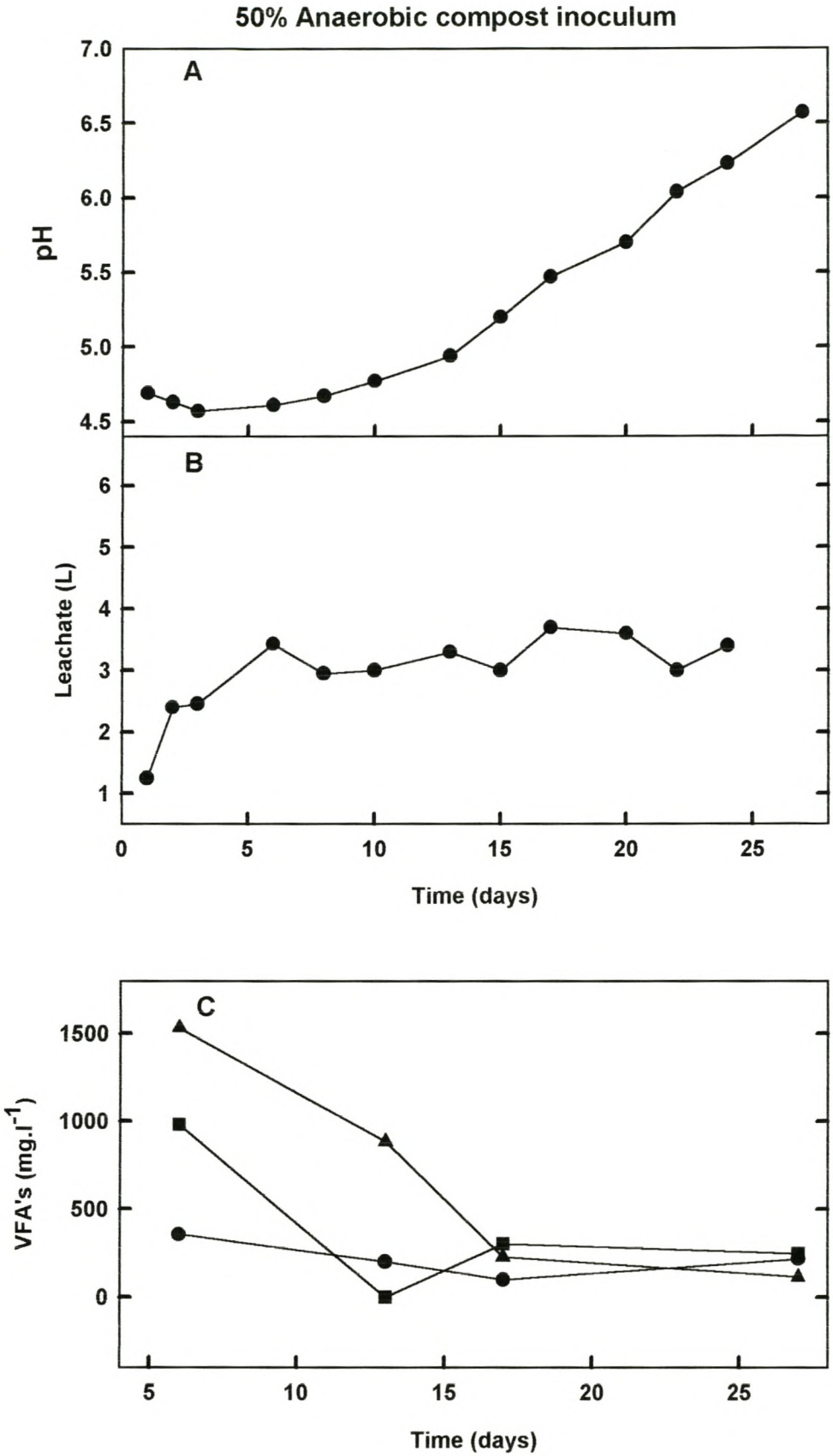

Figure 9. Production of leachate, pH and VFA accumulation when apple pomace and peach pulp was anaerobically composted with 50% (m/m) anaerobic compost inoculum.

compared to the inoculum used in Phase 1. The data obtained are illustrated in Fig. 9A, 9B and 9C. A final pH of 6.8 was achieved at the end of the composting process (Fig. 9A). Large volumes of leachate (average more than 3 L) were removed which probably contributed to the high, final pH of 6.6 that was a result of the removal of large amounts of VFA's (Fig. 9B).

The final concentrations of all the VFA's in Unit 1 were low and this indicated that a good balance had been established between the different micro-organisms, thus leading to a good digesting process (Fig. 9C). The profiles of the VFA exhibited a decrease in the concentrations of the VFA's from the first day of composting. This could possibly be an indication that the micro-organisms were very active during the process. Although the composting period was 26 days, a pH of 6.0 was already achieved after 22 days.

From the results obtained, it was again confirmed that anaerobic compost is an excellent and very suitable inoculum to use. Better results, based on the more neutral and stabile pH value as well as the low VFA's concentrations and the excellent leachate production, were obtained with a 50% (m/m) inoculum compared to a 20% (m/m) inoculum (Phase 1).

Experimental Study 3: *Evaluation of the efficiency of different inoculum sources and a growth factor stimulant on the composting process*

Cattle manure as well as CME, as a growth factor stimulant, were used to try and stabilise the pH earlier during the composting process. The results, using three units, are illustrated in Fig. 10 and 11.

The best increase and stabilisation of the pH were obtained in Unit 2 where fresh cattle manure was used as the inoculum (Fig. 10). The addition of CME did not appear to have had an effect on the pH at first, but during the last few days of the composting process, the pH of Unit 3, with the added CME, reached the highest levels and a final pH of 6.7 was obtained. Unit 1, with the sludge inoculum and CME, only reached a final pH of 6.07.

The volumes of leachate measured were similar for all three units. At start-up very little leachate was produced, but this gradually increased during the digestion of the composting substrate. Although 3 L of 'moisturising liquid' were added every 48 h, leachate volumes around 3.5 L were removed thus indicating

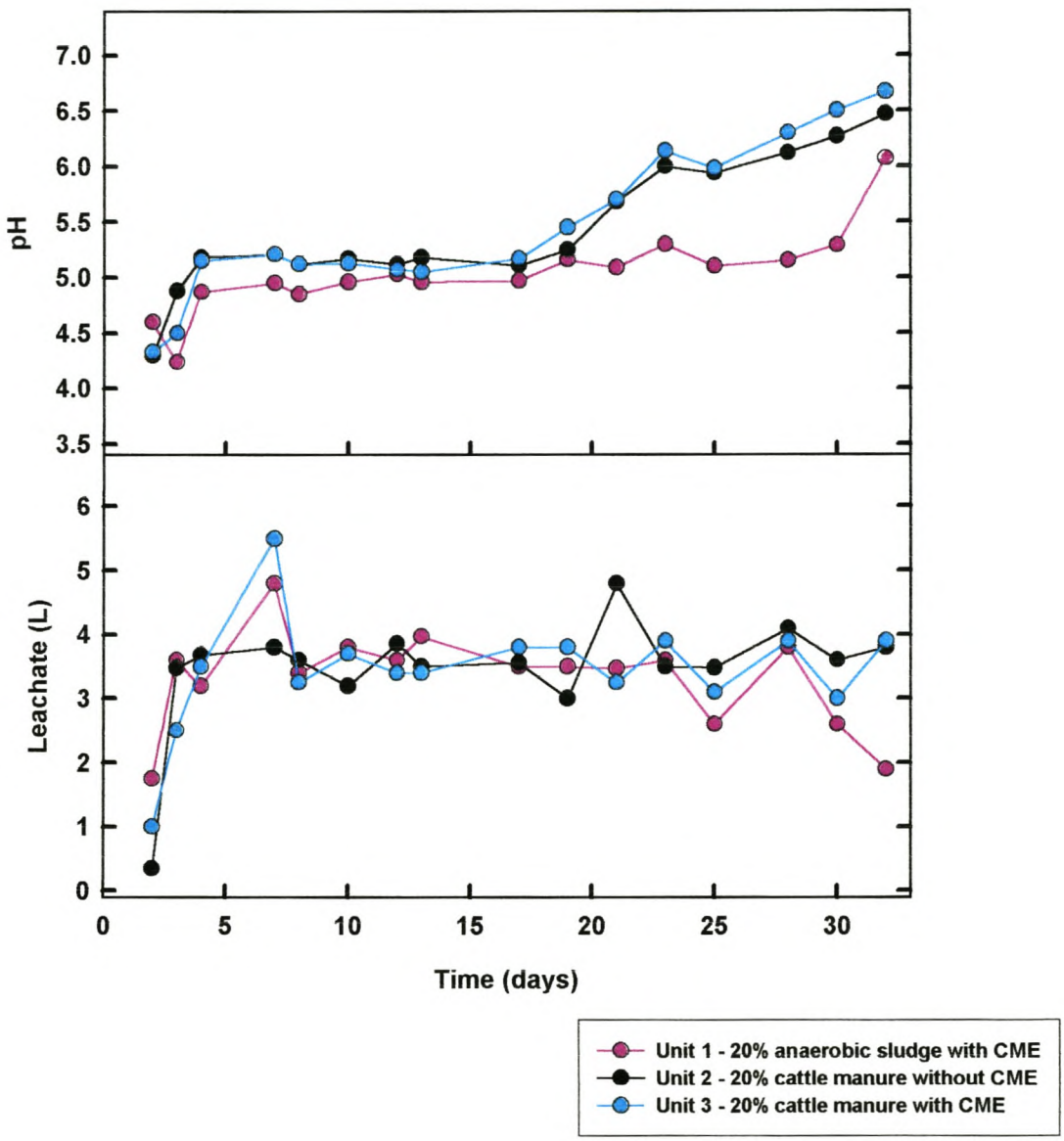

Figure 10 . Production of leachate and leachate pH when apple pomace and peach pulp were anaerobically composted with different inoculums (anaerobic sludge, anaerobic compost and cattle manure with or without cattle manure extract (CME)).

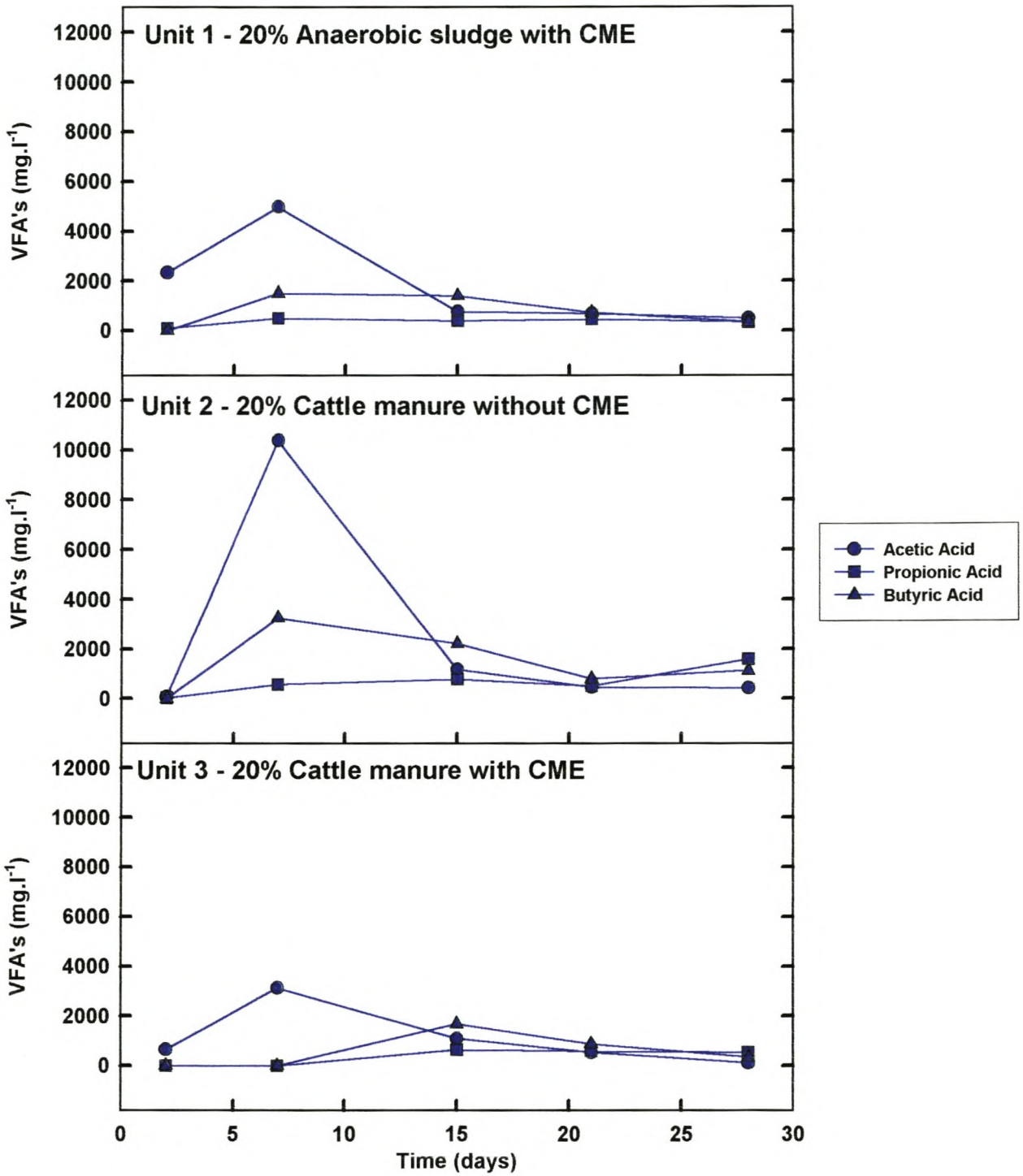

Figure 11. Accumulation of acetic, butyric and propionic acid during the digestion of apple pomace and peach pulp and when different inoculums were used (CME - cattle manure extract).

that the mass of the substrates was being reduced during the process. At the end of the 34 days of composting, the composted substrates were weighed and the percentage volume reduction calculated. The best volume reduction of 59% (m/m) was obtained with Unit 2. Units 1 and 3 had a 51 and 53% (m/m) volume reduction, respectively.

The concentrations of acetic, butyric and propionic acids were determined and the results illustrated in Fig. 11. Overall, Unit 2 produced the highest concentrations of VFA's, followed by Unit 1 and then Unit 3. It was concluded that the added CME to Unit 3 did have a positive affect on the production and removal of the VFA compared to Unit 2 which had not receive CME. In Units 2, the profiles of the VFA's exhibited an increase over the first 7 days followed by a decrease in concentrations. This could possibly be an indication that the micro-organisms were most active during this stage in the process.

From the results obtained, it was concluded that Unit 2 (inoculated with 20% (m/m) cattle manure and no added CME) performed the best when the pH and final VFA's concentration and mass reduction were taken into consideration. However, the results obtained during this experimental study, were still not fully satisfactory, because the overall composting period was too long to be economically feasible.

Experimental Study 4: *Evaluating the efficiency of the composting process when 125 g instead of 250 g $NaHCO_3$ were added as pH stabilisers*

During this study $NaHCO_3$ was added to the composting substrates to try and make the composting process, in terms of the composting period, economically more viable. Two inoculums were compared in this study; 50% (m/m) anaerobic compost and 20% (m/m) fresh cattle manure.

The data obtained are illustrated in Fig. 12 and 13. The pH of Unit 1 was much higher throughout the whole composting period than for the other three units (Fig. 12). A final pH of 6.97 was achieved, while pH values above 6.0 were not obtained for any of the other units. It was concluded that better results were obtained in the Units with additions of 250 g $NaHCO_3$ than when 125 g $NaHCO_3$ were used.

The leachate removal was more or less the same for all the units, starting with less than 3 L removal but within a few days, progressing to volumes higher than 3 L (Fig. 12). The removal of larger volumes of leachate again indicated a volume reduction. A volume reduction of 55% (m/m) was obtained with Unit 1, while the volume reductions for Units 2, 3 and 4 were calculated at 40, 34 and 36% (m/m), respectively. A possible explanation for these lower volume reductions could be that the composting period was too short thus leading to a reduced degradation of the substrate.

In this study the alkalinity was also determined (Fig.12) and the best alkalinity levels were achieved with Unit 1, followed by Unit 3. This could be explained by the larger concentrations $NaHCO_3$ that were added compared to Units 2 and 4.

The leachate-COD results were excellent (Fig. 12). From these results it was again concluded that the 50% anaerobic compost was the better inoculum to use. Although the final COD levels were still very high, 3 950 and 8 500 $mg.l^{-1}$ for Units 1 and 2, respectively, they were lower than the final COD levels of Units 3 and 4. A possible explanation for these results is that the inoculum used in Units 1 and 2 was 50% (m/m) anaerobic compost. This would mean that 50% (m/m) of the substrate was previously composted and the microbial consortiums were well adapted to the anaerobic conditions.

The best VFA removals were obtained in Units 1 and 3, with Unit 1 exhibiting the better final VFA concentration of around 170 $mg.l^{-1}$ (Fig.13). The concentrations of VFA appeared to be accumulating in Units 2 and 3 during the final stages of the digestion process.

Due to the fact that little literature is available on the quality and composition of anaerobic compost, it was decided to have the final compost from the four Units analysed so as to compare the produced anaerobic compost to aerobic compost (Table 1). The moisture content before and after composting was in all cases very high. High moisture content is necessary at the start-up of the composting process to activate the micro-organisms (Minaar, 2001) (Table 1). However, final moisture content of between 60 and 70% (m/m) is required for good quality compost (Minaar, 2001). From the results of the analyses it was concluded that the moisture content of the anaerobic compost produced during

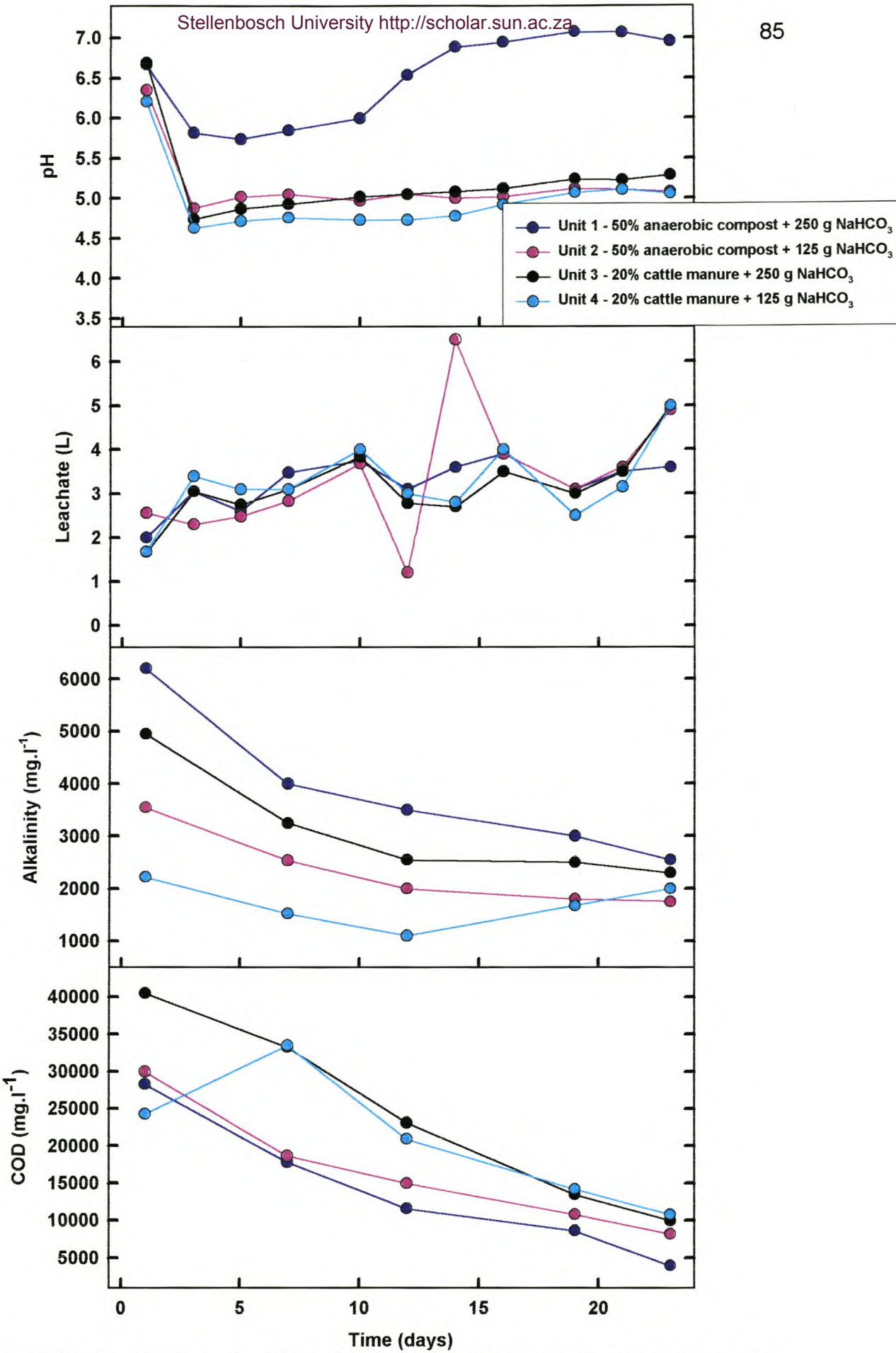

Figure 12. Production of leachate, leachate pH, COD and alkalinity when apple pomace and peach pulp were anaerobically composted.

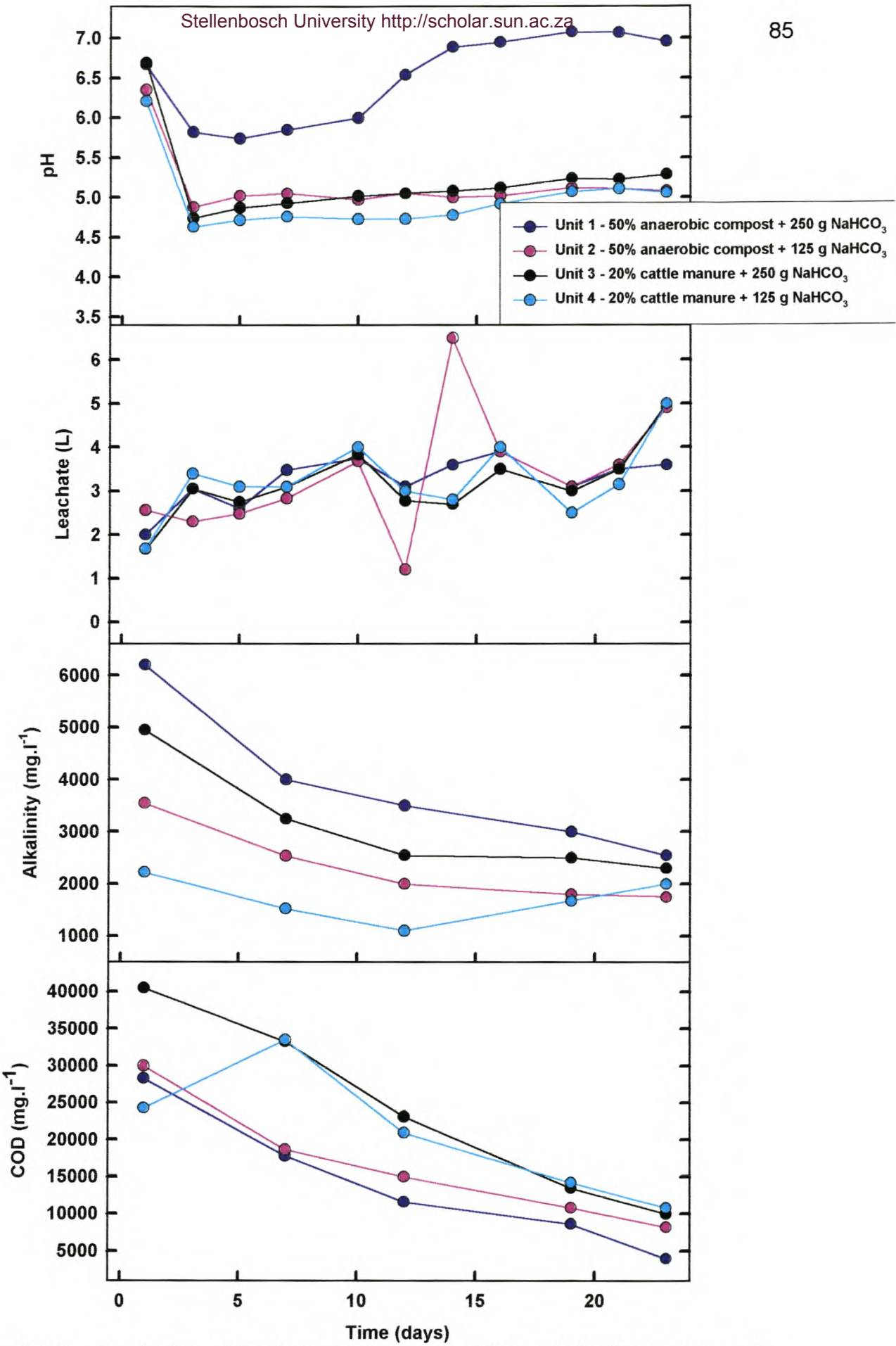

Figure 12. Production of leachate, leachate pH, COD and alkalinity when apple pomace and peach pulp were anaerobically composted.

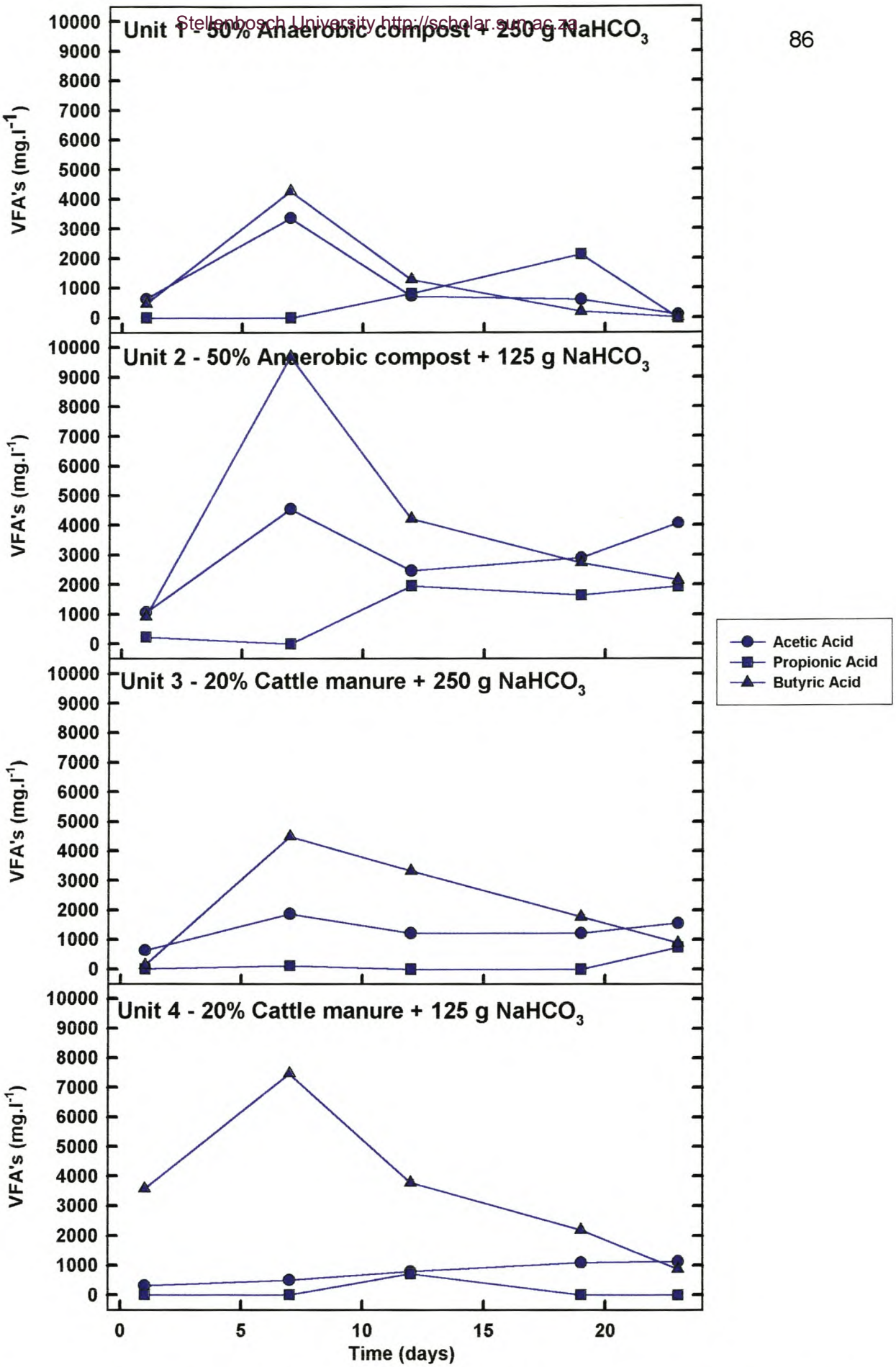

Figure 13. Accumulationof acetic, propionic and butyric acids during the digestion of apple pomace and peach pulp when different amounts of $NaHCO_3$ were used.

Table 1. Composition of the anaerobic compost before and after the apple pomace and peach pulp substrate was anaerobically composted in the 20 L composting units.

	Before composting				After composting			
Unit No.	1	2	3	4	1	2	3	4
Moisture (%)	82.7	82.0	93.7	82.5	82.4	80.4	85.8	84.9
pH	5.6	5.6	5.2	5.1	7.3	7.1	6.9	6.8
N (%)	1.7	1.5	1.2	1.1	2.7	2.5	2.3	2.6
Cu ($mg.l^{-1}$)	1.8	1.3	0.9	0.8	3.6	3.5	3.4	2.8
Mn ($mg.l^{-1}$)	14.0	11.2	4.7	3.9	9.7	7.6	3.8	3.4
Zn ($mg.l^{-1}$)	15.2	7.4	3.2	3.1	25.3	13.9	5.2	4.3
P ($mg.l^{-1}$)	67.3	59.7	78.6	66.4	26.0	30.2	55.3	52.6

this study was in all cases on the high side. The moisture content after composting was found to be only slightly lower than before composting. Unit 3 exhibited the largest difference in moisture content of all four Units.

The pH of the final compost was satisfactory as a final pH of between 6.0 and 7.0 is required for a good quality compost (Minaar, 2001) (Table 1). The pH values were higher after composting. The pH of Unit 1 was the highest (Table 1). The pH values of the anaerobic compost were found to correlate well with values reported for the Sequential Batch Anaerobic Composting (SEBAC) system developed by Prof. Chynoweth at the University of Florida (Anon., 1997). From the results obtained in this study it was concluded that Unit 1 performed the best.

Experimental Study 5: Optimising the $NaHCO_3$ addition

This study was to determine the best concentration of $NaHCO_3$ to be added to the composting substrates and still obtain a good pH stabilising effect. Cattle manure was also included as an inoculum to determine if it could be successfully used as an inoculum to anaerobically compost solid fruit wastes.

The results from this study are illustrated in Fig. 14 and 15. The pH profile of Unit 2 (50% (m/m) anaerobic compost and 250 g $NaHCO_3$) was found to be very similar than that of Unit 1 (50% (m/m) anaerobic compost and 200 g $NaHCO_3$) (Fig. 14). Units 3 and 4, where 20% (m/m) cattle manure was used as inoculum did not perform quite as good as Units 1 and 2, but even so, final pH values of >6.0 were obtained.

The leachate removal profiles were similar for all four units and again, as in the previous studies, within a few days a reduction in volume was observed as more leachate was removed than was added to the units (Fig. 14). Based on the leachate production, the composting process of these four units was successful. Initially, at start-up, all the components of the substrate were easily recognisable and the leachate that was removed had a bright yellow colour. The substrate also had a very prominent, sour smell of rotten fruit. After about 6 days of composting, the leachate of Unit 1 had a dark green colour while the colour for the other three Units only changed after 10 days. After 15 d of composting, the colour of the leachate from all the Units was dark brown and the compost material had a more acceptable smell. When the units were finally opened after 25 d, the compost had an even dark colour and the fruit components were not identifiable.

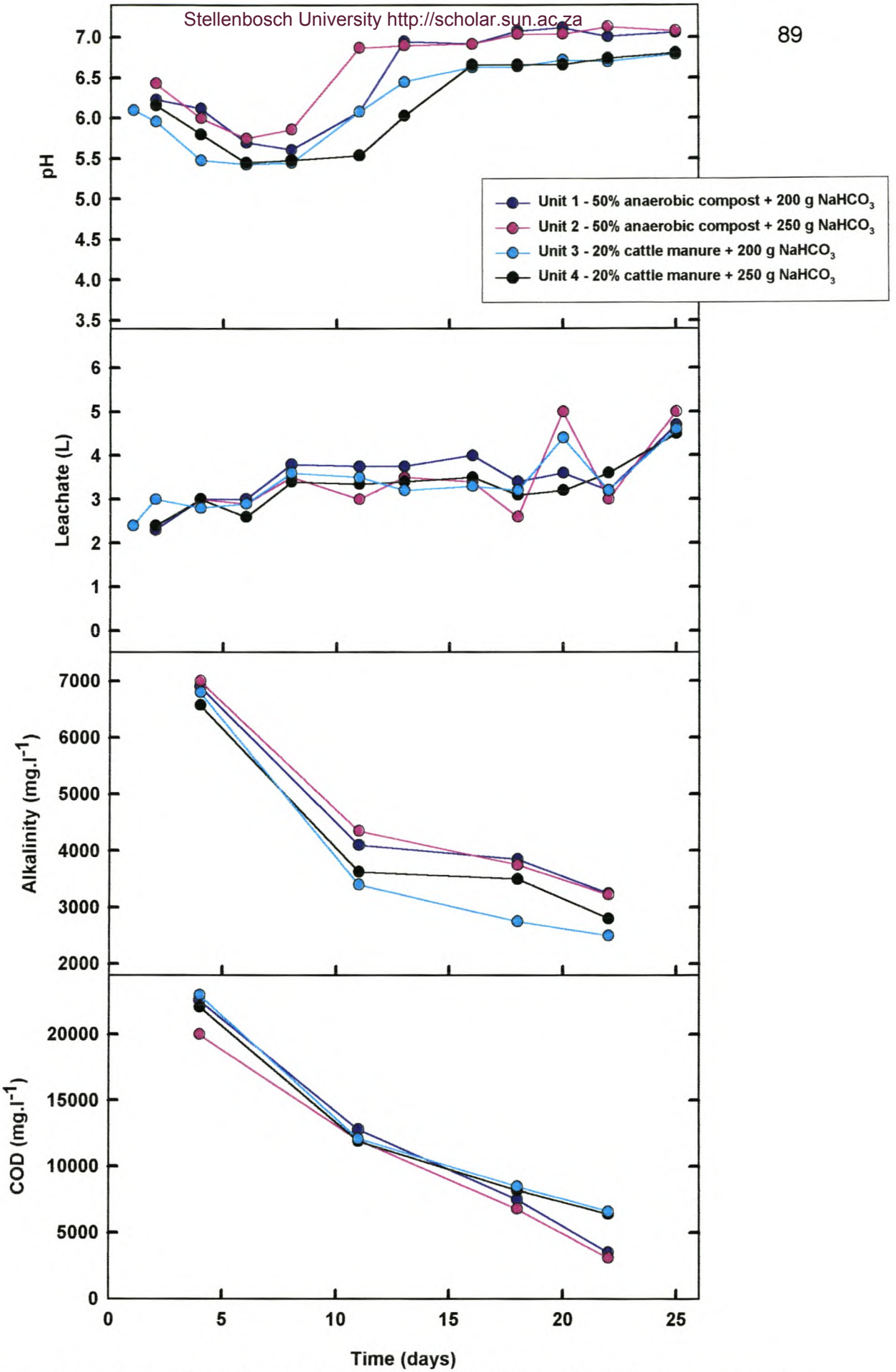

Figure 14. Production of leachate, leachate pH, COD and alkalinity when apple pomace and peach pulp were anaerobically composted.

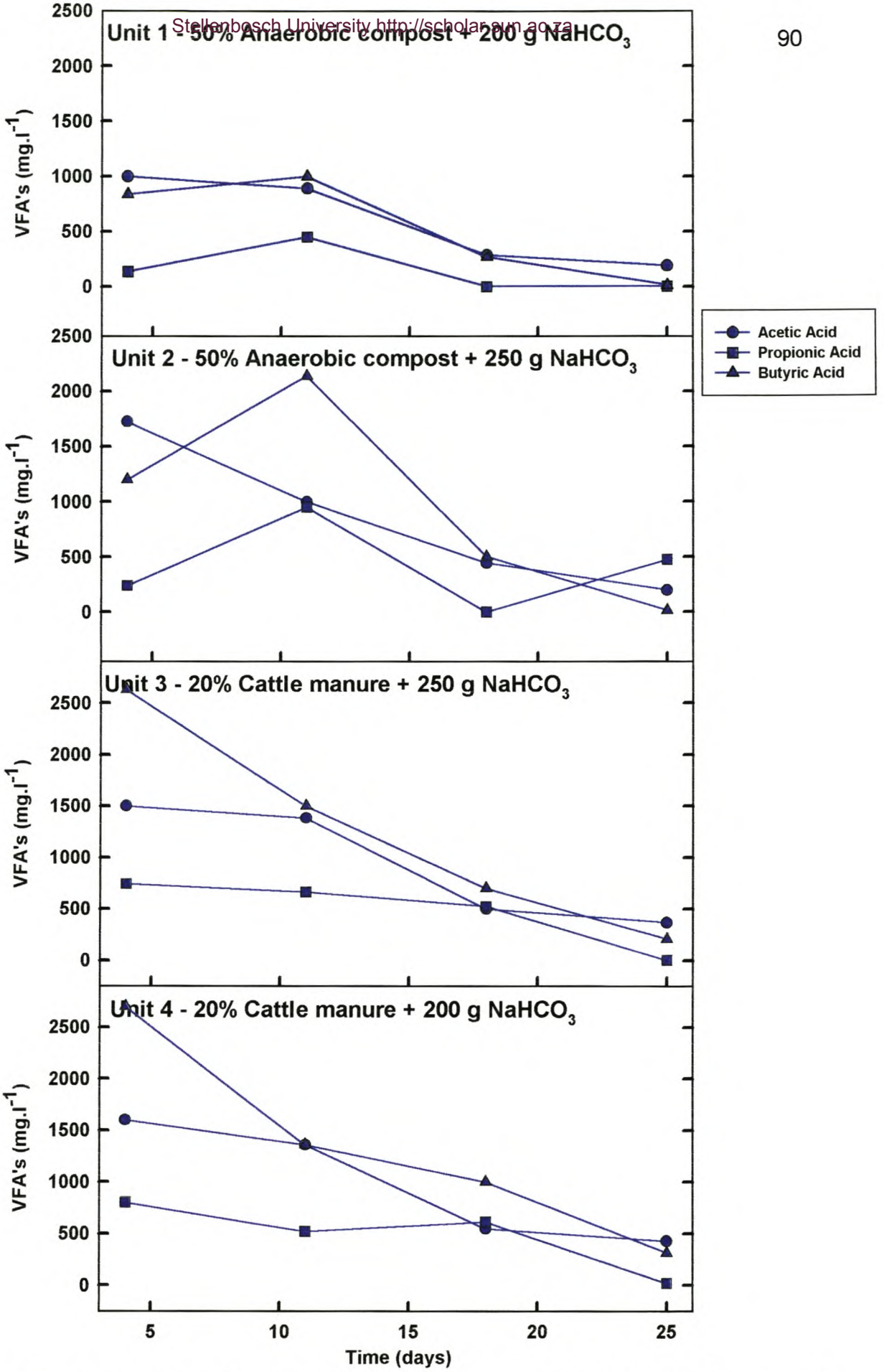

Figure 15. Accumulation of acetic, propionic and butyric acids during the digestion of apple pomace and peach pulp when different concentrations $NaHCO_3$ were used.

An acceptable volume reduction was found for all the units with Unit 1 giving a 50% reduction in original substrate volume while Units 2, 3 and 4 resulting in a 66, 54 and 65% reduction, respectively.

The average alkalinity was the highest for Unit 2 throughout the duration of the composting process with a final value of 3 900 $mg.l^{-1}$. The reduction in COD was the best for Units 1 and 2 with a final COD concentration of 4 100 $mg.l^{-1}$ being achieved in Unit 2 (Fig. 14).

The final values of the VFA concentrations were much lower than previously obtained and it was found that the VFA's did not accumulate and were either used by members of the microbial consortium or removed via the leachate (Fig. 15). The result of this was that the concentrations were low and never reached the high values that were found in previous studies.

It was also of interest to note that the pH of the leachate removed from the units in this study did not need to be adjusted before feeding to the UASB bioreactor. In turn, the effluent from the bioreactor was re-added back to the composting units without pH adjustment. These pH results indicated that the composting units and the bioreactor could be operated in perfect mutualism.

After evaluating all the results obtained in this Experimental Study, it was concluded that all four Units could be used for further scaling-up. If one unit has to be selected, it would be Unit 2, but when economical factors need to be strictly considered, the best results were achieved with Unit 4. Although this unit did not perform as well as the other three, the results were still very acceptable.

Conclusions

As literature on anaerobic composting research is very limited, it was decided to develop a scaled-up method based on empirical methods. Therefore different experimental studies were undertaken and the most efficient unit of each study served as a starting point for the following study. In this way, unit and set-ups that were not efficient, were excluded and finally a combination was found for the anaerobic composting of apple pomace and peach pulp that led to a satisfactory final product.

After conducting these Experimental Studies, several important conclusions were made. After performing Study 1, it was concluded that a mixture of apple

pomace and peach pulp could be use as a substrate for anaerobic composting. The results obtained in this Study compared excellently with results obtained in Chapter 3. Special 20 L PVC units were built and used in the scaling-up of the anaerobic method, which was developed in Chapter 3 and also tested again in Study 1 of this Chapter by using peach pulp with apple pomace.

Study 2 was performed by directly scaling-up the method used to perform Study 1 and a very important conclusion was drawn from the results obtained in Study 2. It was concluded that the scaled-up method did not produce as excellent results as it did when 2 L glass bottles were used. It was thus necessary to adjust the existing composting method to better suit the needs of a scaled-up method. A second phase of Study 2 was performed and this proofed to be of great value.

A 50% (m/m) anaerobic compost inoculum was used and from the results it was concluded that this was a better inoculum to use. In the strive to achieve better results cattle manure and cattle manure extracts were used as inoculum and growth stimulant, respectively. Although some improvements were recorded with the use of cattle manure as an inoculum, no real progress was made when cattle manure extract was added to the substrate to be composted. Anaerobic compost appeared to be the best inoculum to use in the composting process.

Additions of $NaHCO_3$ were made in another attempt to obtain a faster and better pH stabilisation. Very good results were obtained and it was concluded that, although slightly better results were obtained with additions of 200 g of $NaHCO_3$ was adequate to used when economical aspects was taken into consideration. Finally a scaled-up method was developed with a 50% (m/m) anaerobic compost inoculum and additions of 200 g of $NaHCO_3$.

Due to a lack of adequate equipment, it was impossible to measure the biogas production. Rubber tubing was, however, connected from the composting units to a measure cylinder filled with water. By displacements of large volumes of water with gas, it was concluded that biogas was produced in large amounts

The UASB bioreactor and the composting units were operating excellent and in the final stages of the research it was found that it was not necessary to make any pH adjustment to either the UASB affluent that was re-added to the composting units or the leachate that was fed to the bioreactor.

A final composting period of 25 d was achieved. By observation its was further concluded that large volumes of biogas were produced, but due to a lack in

the proper equipment and leakages form the composting units, this could not be measured.

The general conclusion made from the results obtained in this study is that the UASB bioreactor and the composting units were operating in a symbiotic manner. Furthermore, it was concluded that it was indeed possible to anaerobically compost solid fruit wastes from the processing industry, with the joint advantages of biogas production and compost generation. In future it would be advisable to do research on the application of anaerobic compost. It would also become necessary to obtain suitable equipment to measure the volume biogas that is produced during the process.

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CHAPTER 5

GENERAL DISCUSSION AND CONCLUSIONS

South Africa is a developing country that, especially in the Western Cape Province, relies heavily on its agricultural sector for economical welfare. However, development gives rise to new technology, new products, economical stability and unfortunately also the production of larger volumes of liquid and solid wastes.

The fruit processing industry is a large division of the processing industry and during the 1999/2000 season, 241 084 tons of fruit (apricots, peaches and pears) were processed. The disposal of solid fruit wastes has become a major concern to many South African fruit processing factories, as disposal regulations are becoming more stringent. As a result, traditional disposal methods are becoming inadequate to handle the volumes and may even be responsible for further serious environmental pollution problems.

Many fruit processing factories are currently selling the fruit pomace and pomace to farmers for the use as animal feed. In the past this has contributed in partially solving the problem, but with the continuously growing demands of the consumers, factories are processing more and more fruit each year, thus creating more solid waste. When taking the financial expenses of solid waste disposal and the generation of heat for these factories into consideration, it has become necessary to develop new technologies to aid the management of solid wastes. Anaerobic composting is one such new technology that could benefit solid waste disposal in the factories.

The objective of this research was to develop a method to anaerobically compost apple and peach pomace. In the first part of this study, important operational parameters were identified and a method was developed to optimise the control of these parameters. In the second part of the study, the scaling-up and optimisation of the process were the major objectives.

The first operational factor that was considered in the study was the use of different inocula and the application ratio applied to the substrate. The type and source of inoculum are important in the digesting process, as the microbes present are directly responsible for the active microbial community necessary to digest the substrate.

During certain of the studies (Experimental Studies 1 and 2 of Chapter 3 and Study 4 of Chapter 4), high concentrations of volatile fatty acids (VFA's), final values which exceeded 5 000 $mg.l^{-1}$, were produced. It was concluded from these studies that the accumulation of VFA's when not removed, caused composting failures sometimes referred to as 'sour' fermentation or acidification. Based on the data obtained it was decided to remove the produced leachate during the composting process, thus also removing the accumulated VFA's. Propionic, butyric and acetic acids were the major acids produced. The removed leachate was then used as substrate for an UASB bioreactor, in which the microbial consortium was adapted to successfully remove large concentrations of VFA's. The effluent from the UASB bioreactor was subsequently re-added back into the composting units.

Control of leachate pH as an operational parameter was also found to be essential in all conducted studies. Different operational parameters were investigated during the different studies to identify the most suitable and economical attractive method to control and stabilise the pH. The first action was to wash the pomace with water, but this is not a very practical method when scaling-up is considered, as water is scarce and a new polluted effluent is generated. Secondly, the liquid fraction of the 'raw' pomace was removed by pressing it per hand. The pH of the liquid fraction was then adjusted before re-adding to the solid fraction. For practical reasons this method would be inadequate when large volumes of fruit wastes need to be composted. Finally, the possibility of using an UASB bioreactor to re-circulate the leachate from the composting units was investigated. In this study, the leachate from the composting units was added as substrate to the UASB bioreactor and the subsequent UASB effluent, at a more suitable composting pH of ±6.5 was re-added into the composting units to provide the necessary moisture. The UASB bioreactor was thus successfully used to control the pH in the composting units by removing the accumulated VFA's and thus subsequently, if necessary, adjusting the pH to higher values to better aid the composting process when the effluent was re-added to the units. An additional advantage of this method was the continuous addition of fresh and active anaerobic microbes from the UASB bioreactor to the composting units through the UASB effluent.

Another aspect that was identified as a critical operational parameter that had to be carefully controlled and optimised, was the moisture content of the substrate at initial start-up period. Different 'moisturising liquids' were thus evaluated to provide optimum moisture levels during the composting process. From the results of Experimental Study 3 (Chapter 3), it was concluded that UASB bioreactor effluent was the best 'moisturiser' to use. Final concentrations of VFA's of between 84 and 30 $mg.l^{-1}$, for acetic and butyric acids, respectively were measured, while large volumes of biogas (values exceeding 45 ml) were also measured.

The start-up moisture content in the digestion units was also taken under consideration as an important operational parameter. From the results of Experimental Study 2 of Chapter 3, it was concluded that better results were obtained when the moisture content at start-up was 60% or higher (m/m). Biogas production was the highest (total biogas production of 778 ml per unit) when the moisture content was higher. High moisture contents of the substrate also appeared to benefit the pH of the composting process as higher final pH values were obtained.

After developing a lab-scale method to compost apple pomace anaerobically in 2 L glass containers, the next step was to ascertain if the method would work if larger volumes of solid fruit waste were composted. It was also decided to mix apple pomace and peach pulp together and to use it as part of the composting substrate. Peach pulp and apple pomace are fruit wastes that are produced in large amounts in the Western Cape Province and it presents a real problem for the future.

Currently, little literature is available on anaerobic composting of solid fruit waste and consequently most of the studies were started on anaerobic liquid digestion studies. For the scale-up studies, the most important operational parameters (pH stabilisation, inoculum size and moisture addition) from the 2 L composting units were again used as reference. Different inoculums were used, including cattle manure, anaerobic sludge, brewery granules and anaerobic compost produced in the previous tests. Although good results were obtained when anaerobic compost and cattle manure were used as inoculums, the aim was to decrease the composting period by achieving a faster pH stabilisation. To achieve this it was decided to add different concentrations of $NaHCO_3$ to the

substrate to be composted to achieve faster pH stabilisation. By adding 250 g $NaHCO_3$, the composting process reached a final pH of between 6.0 and 7.0 in a shorter time period, thus making the composting process faster. Although good results were obtained when the large amounts of $NaHCO_3$ (250 g/15 kg substrate) were used, a further aim was to make the process economically more feasible by scaling down the bicarbonate addition. In the subsequent study a lower $NaHCO_3$ addition (125 g/15 kg substrate) was used. Good results were obtained after the leachate pH and concentration VFA's, produced during the study, were evaluated graphically.

An UASB bioreactor was also used in this 'scale-up' research to aid the composting process by converting the VFA's in the leachate removed from the composting units to more suitable compounds before it was re-added to the units. During these studies it was found that when the bioreactor was fully operational it was not necessary to make any pH adjustment to either the UASB effluent that was re-added to the composting units or to the leachate from the composting units that was fed to the bioreactor as substrate. Thus, the bioreactor was stable enough to use the leachate from the composting units, with an average pH of between 3.5 and 5.5 with a COD value of ±3 500 $mg.l^{-1}$ and to convert it to a suitable 'moisturising liquid' that was re-added to the composting units, with a pH of 6.5 – 7.0.

During the final Experimental Study (Study 5, Chapter 4), a composting period of 25 days was achieved with a final compost pH of >6.5 and COD values that were drastically reduced from >20 000 $mg.l^{-1}$ to ±5 000 $mg.l^{-1}$. The reduction in the concentration VFA's was also significant and final values of less than 500 $mg.l^{-1}$ were measured.

The general conclusion made from the data obtained in this study was that with an UASB bioreactor and composting units operating in a symbiotic manner, satisfactory pollution control could be obtained. Furthermore, it was concluded that it was indeed possible to anaerobically compost solid fruit wastes from the processing industry, with the joint advantages of biogas production and compost generation. However, for future research it will be necessary to evaluate the quality of the anaerobically produced compost as a soil conditioner. In terms of utilising the biogas as a valuable energy source, it will also be necessary to develop suitable equipment to measure and collect the biogas that is produced

during the process. If further scaling-up is to be considered, it might be more appropriate to couple the composting unit directly to an UASB bioreactor, thus making the process continuous and more practical to operate. If the anaerobic composting method could be improved in such a way that the process could be used for treatment of difficult types of solid fruit wastes, it would probably be more advantageous for the fruit processing industry to use as an environmental control technology.