Use of Vermicomposting in Domestic Onsite Sewage and Biowaste Management

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DEDICATION

To my mother, Dr. Shyamala K. Panikkar

for all the love, encouragement, support and prayers

To the memories of my father Dr. K. Kesava Panikkar
Who left me in the third year of my research
For the inspiration and encouragement
For all the practical skills
For introducing the nature to me
For creating a love for the environment
For making me what I am

And

To the memories of my grandmother P. T. Parvathiamma
who gave me the first lesson
in biological waste treatment 25 years ago.

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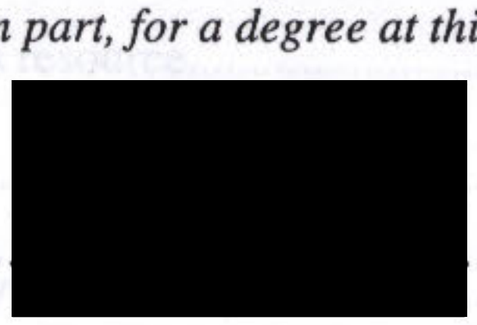
Statement of Authentication

The work presented in this thesis is, to the best of my knowledge and belief, original except as acknowledged in the text. I hereby declare that I have not submitted this material, either in full or in part, for a degree at this or any other institution.



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ABBREVIATIONS USED

AD – Anaerobic Digestion

ADP – Adenosine Diphosphate

AGAL – Australian Government Analytical Laboratory

ANS – Anthropogenic Nutrient Solutions

APHA – American Public Health Association

AS 4454 – Australian Standard 4454

AS/NZS - Australian and New Zealand Standard

ATP – Adenosine Triphosphate

BAF – Biological Aerated Filter

BOD - Biochemical (Biological) Oxygen Demand

BOD_5 – 5-day Biochemical (Biological) Oxygen Demand

C: N – Carbon to Nitrogen Ratio

CFU – Colony Forming Units

COD – Chemical Oxygen Demand

DO – Dissolved Oxygen

EC – Electrical conductivity

FD – Forced Draft

HDPE – High Density Polyethylene

HRT – Hydraulic Retention Time

ID – Induced Draft

ISWM – Integrated Solid Waste Management (hierarchy)

MABR – Membrane Aerated Bioreactor

MBR – Membrane Bioreactor

MPa – Mega Pascal

MSW – Mixed/Municipal Solid Waste

NATA – National Association of Testing Authorities, Australia

NSCA – National Safety Council of Australia

NSW – New South Wales

NTU – Nephelometric Turbidity Units

OHS – Occupational Health and Safety

PVC – Poly Vinyl Chloride

QA/QC – Quality Assurance / Quality Control

ROU – Recycled Organics Unit

SBR – Sequential Batch Reactor

SCOD – Soluble Chemical Oxygen Demand

SRT – Solids Retention Time

SS – Suspended Solids

TDS – Total Dissolved Solids

TKN – Total Kjeldahl Nitrogen

TN – Total Nitrogen

TOC – Total Organic Carbon

TP – Total Phosphorous

TSS – Total Suspended Solids

UOD – Ultimate (Total) Oxygen Demand

UV – Ultra Violet radiation

UWS - University of Western Sydney

VCU – Vertical Composting Unit

VFA – Volatile Fatty Acids

WHO – World Health Organization

ABSTRACT

Modern lifestyle has increased the amount of solid and liquid waste that humans create. There are issues associated with pollution and disposal. The tried and tested methods of centralised treatment have proven impractical in the long run, given the spread of human population. Moreover, such techniques are unsuitable for the developing and under-developed world due to huge infrastructure costs and lack of technology issues. Adaptation of technologies from the developed world often does not provide the required solutions.

This thesis describes an attempt at finding an ecologically and economically sustainable solution for waste management that is appropriate for poorer regions and remote areas. The proposed treatment system is close to natural processes and uses biological waste processing methods that have proven to be sustainable. Available resources and low cost give an edge for such processes to be practical and realistic. The system is based on vermicomposting. Composting worms survive in the harsh environments found in most parts of developing world.

A working prototype of the vermicomposting waste management system was designed to utilise the technique of vermicomposting to treat putrescible fraction of domestic solid wastes along with pathogen-rich human excrement wastes (blackwater). Tests with organic solid wastes and liquid pig manure (as a replacement for blackwater) yielded excellent results in terms of reduction in pollutant loading such as suspended solids, turbidity, Biochemical and chemical oxygen demands, faecal coliform and ammonia content. Areas for further research and process optimisation were identified that would pave way for future endeavours towards development of a fully working model. The treatment system is shown to work and achieve the objectives of treating waste to usable products including worms for feed supplement, compost fertiliser and irrigation water.

CHAPTER 1 - INTRODUCTION

"The world we live in has more problems now than that can be solved by thinking the way we did when we created them"

-Albert Einstein

1.1 Introduction

Nowhere else is the above quote more evident and obvious than our environment and our basic lifestyle. The air we breathe, the land on which we walk and cultivate our food, the water we drink and bathe in, and even our fellow life forms and ourselves are affected by our own deeds. There is a need for alternate ways of thinking and acting with our environment, lest we make things worse in the future.

Many environmental problems come from different forms of waste created from our lifestyle and economic development. Industrial and automotive emissions create acid rains and breathing problems while industrial and commercial liquid effluents create groundwater and surface water pollution. Solid wastes are creating problems in terms of demands for disposal space and water pollution through leaching (Figure 1.1).

Technologies exist and are continuously developed for managing waste, but at times it seems that the magnitude and evolution of waste outrun the solutions. The fast pace of population growth, change in lifestyles and increased use of resources have magnified waste generation. Many of the issues of waste generation are localised and need localised treatment options, as centralised treatment of waste is not always the

most efficient approach. Sustainable development and appropriate technology have become primary parameters for choosing and developing technologies. What works for cities may not work for rural areas and what works for the developed world may not be appropriate for developing or under-developed nations. Research is necessary to find ways to deal with specific problems in specific regions [Jain 1994; Aranda *et al.* 1999; D'souza 1999; UNFPA 2001].

Figure 1.1 Solid waste dump in India

(*Photo courtesy Environmental Support Group, Bangalore)*

1.2 Research Problem

This thesis approaches two main areas of domestic waste generation – water and solids - with the focus on finding usable products from treatment of wastes. Fresh clean water is a limited resource around the world – its absence can lead to environmental and human health problems. Various water-conserving technologies are being advertised and used, but there still is room for improvement [Gleick 2000].

Many new 'technologies of the future' for delivering potable water are reported and being researched, but these remain ‘technologies of the future’ and are unlikely to

have widespread utility in the immediate future. The huge quantity of solid waste generated in industrialised countries and fast-developing economies is another issue. The usual final disposal option of landfills is becoming more and more impractical due to scarcity of sites, costs and management problems.

The ISWM (Integrated Solid Waste Management) hierarchy advocates that all waste management options should work in conjunction with each other, with the ultimate aim of optimum waste reduction and pollution control [Bluestem 1997a, 1997b]. The hierarchy recommends the options of waste management, in the order of preference, as:

- Source reduction
- Maximum utilisation
- Reuse - recycling including composting
- Incineration with energy recovery
- Incineration without energy recovery and
- Landfilling.

Human waste is a major source of nutrients and energy that can be tapped, as demonstrated in some ancient cultures. In the modern world, flushing toilets are the norm, which adds significant quantities of wastewater (blackwater) to the waste stream. Studies have progressed in the direction of extracting fuel out of waste treatment technologies, mostly using anaerobic methods [Imura *et al.* 1995; Harremoes 1997; Jefferson *et al.* 2000]. The process of composting, which is an aerobic process, creates heat and converts solid wastes into compost that can be used as a fertiliser [Haug 1993; Hoitink and Keener 1993]. Whether done with microbes

and/or worms, the process goes through similar stages and the end results are mostly the same [Haddon 1993].

This thesis is focused on an appropriate, composting-based technology that can be adapted to various standards of domestic dwellings for managing both solid and liquid wastes. The possibility of utilising the processes of composting technology for the treatment of blackwater is studied.

The **hypothesis** of the thesis is that a low cost – low maintenance system for domestic onsite waste management is viable, and it can be incorporated within a total waste management programme.

1.2.1 Aims and Objectives

This research project integrates the technology of wastewater management and solid waste management in order to provide a treatment option for 'blackwater'. The processes of composting, microbial and worm action, as well as generated heat provide an opportunity to convert biodegradable household wastes and blackwater to compost and usable water. Blackwater that has been well treated by the composting technology should be safe enough to mix with greywater (all domestic wastewater excluding blackwater) to then produce good quality water after further treatment. If the entire biodegradable waste and wastewater at houses can be converted into reusable compost fertiliser and good quality water, then a total waste management system has been developed. Such a technology can be adapted to small commercial establishments and residential complexes [Dixon *et al.* 1999a; Biala 2001; Louhelainen *et al.* 2001].

The aims of this research project are:

1. Devise an appropriate technology of saving and reusing as much water as possible that can be adapted to most types of human settlement, at the same time offer a solution for problems with solid waste management.
2. Devise a process to utilise composting to treat blackwater to greywater standards and at the same time treat solid waste.
3. Design, construct and monitor equipment, which is scalable, for blackwater treatment through composting and further treatment.
4. Analyse risks and suggest guidelines for managing the treatment system.
5. Ensure compliance with relevant regulations and guidelines.

1.3 Water, our most precious resource

Of all the world's water, only 2.5% is freshwater suitable for consumption and industrial and agricultural uses. The remaining 97.5% is in our oceans and seas [Singh 1992]. 87.3% of the freshwater is in polar ice caps and glaciers, 12.3% is stored underground and only 0.4% water is available on the surface and atmosphere of earth. Thus, less than 0.01% of all water is suitable to sustain life on earth (Figure 1.2). Domestic water usage is only a very small part of the total water demand. Major demands are in agriculture followed by industry.

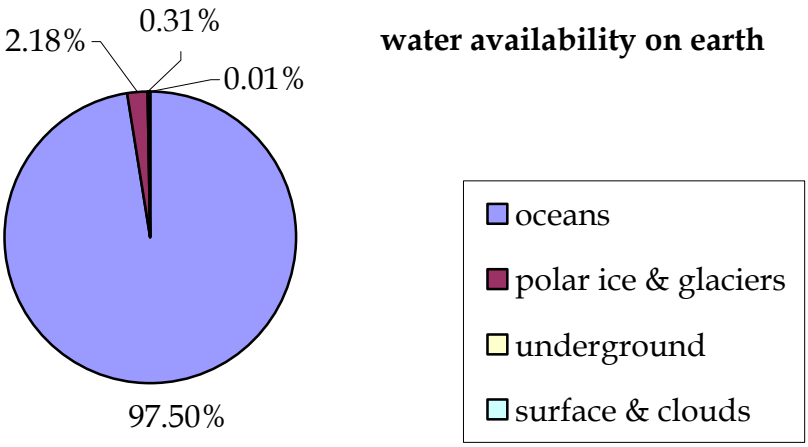

Figure 1.2. The amount of water available for sustaining life

Per capita fresh water use is less in less developed countries than in the more developed countries. The world's water consumption has increased with time but faster than the increase in population. Consumption increased from 580 km^3/yr. in 1900 to 3700 km^3/yr. in 2000 [Gleick 2000], which is more than a six fold increase. During the 1900-2000 period, the world's population increased 4 fold [y6b]. This per capita increase is mainly due to changes in lifestyle and increased industrialisation. Table 1.1 gives average daily use of water for different purposes.

Table 1.1: Average Domestic Water Use (In-house uses)

Water use	*Percentage of total water used*
Toilet flushing	40
Bathing	30
Laundry	15
Kitchen	10
Other	5

Source: Droste, 1997.

1.4 Wastewater Treatment

The history of sewage treatment systems dates back to 1700 BC, in palaces where treated wastewater was used in irrigation [Berry 2001]. Technologies have changed with our development into a modern society and different preferences and there are now many treatment systems. Many approaches have been tried and tested for purification of wastewater and studies have been reported for decades [Barwise 1904]. As Gleick (2000) describes, a new way of thinking is unavoidable in managing our water resources and the way we use water.

Water demands, utilisation and availability differ among regions and communities depending on the geography and lifestyles. It is not possible and realistic to create a common water management programme for all walks of life, but appropriate technology water management programmes need to be developed for different circumstances. Generally, residential wastewater output can be differentiated into greywater and blackwater, and include ANS (Anthropogenic Nutrient Solutions).

1.4.1 Blackwater and Greywater

The major source of wastewater from residential and commercial complexes and institutions is greywater, which is the effluent from washbasins, laundries, bathrooms and kitchens. Some reports can be found that exclude kitchen sink effluent from the definition, owing to the high content of nutrients and suspended solids and defined as blackwater or even termed brown water [Ludwig 2000]. Greywater with heavy contamination or suspended solids has been termed 'dark grey water' for identification purposes in some scientific studies [Ludwig 1994]. Blackwater is the effluent from toilets and has high amounts of suspended solids and

a very high pathogen concentration. Laundry effluent from houses and institutions with infants and ill people can be considered to have higher than normal pathogen levels, but under normal conditions, only toilet effluent is termed blackwater.

Blackwater is a major problem, as it has to be collected and treated lest it becomes a health hazard. The quantities of blackwater created per capita vary between various cultures and places, depending on the particular life style. In most urban areas, a combined sewer is used to carry away the residential greywater and blackwater together for treatment at centralised treatment facilities [Salvato 1992; Salvato and Beck 1994].

The differences between greywater and blackwater are well documented. The amount of nitrogen, pathogens and other pollutants are far less present in greywater compared to blackwater. The [1]BOD_5 for greywater is 90% of [2]UOD compared to 40% for blackwater [Lindstorm 2000a]. This means that greywater is far less polluting compared to blackwater in the long run, as the BOD of greywater more quickly depletes compared to blackwater. Kitchen sink water contains more nutrients and possibly more suspended solids than other forms of greywater. In terms of pathogens and other specific constituents, kitchen sink water can only be defined as greywater, not blackwater. Greywater allows easy and faster treatment compared to blackwater, which needs more intense treatment due to its high [3]COD and microbial

[1] BOD_5 = oxygen required for the decomposition of the organic content in greywater during the first 5 days, determined as BOD after a 5 day period of incubation under standard conditions.

[2] UOD = Ultimate (Total) Oxygen demand in a sample taken.

[3] COD = Oxygen demand for all chemical (organic and inorganic) activities, a measure of organics.

content [Hammes *et al.* 2000]. The COD of domestic wastewater could be as high as 5000-6000mg/l [Dixon *et al.* 1999b]; [Haug 1993].

Table 1.2: A comparison of greywater and blackwater

Parameter	Greywater	Blackwater	Grey+black
BOD_5 (g/p/d & mg/l)	25 & 150-300	20 & 2000-3000	71
BOD_5 (% of UOD)	90	40	-
COD (g/p/d & mg/l)	48 & 300	72 & 2000-6000	-
Total P (g/p/d & mg/l)	2 & 4-35	1.6 -	4.6
Total N (g/p/d)	1 (0.6-5 mg/l)	11 (main source urine)	13.2
TSS (g/p/d)	18	>50	70
Pathogens	Low	Very high	Very high
Main characteristic	Inorganic chemicals	Organics, pathogens	Inorganics, organics and pathogens.

Note: g/p/d: gram/person/day.

Sources: [Haug 1993; Droste 1997; Dixon *et al.* 1999b; Hammes *et al.* 2000; Lindstorm 2000a, 2000b].

1.5 Solid waste management

Wastewater management should be planned in conjunction with a total waste management strategy, after considering all needs and environmental aspects that relate to the issue of waste. The quality, quantity and classification of wasted matter are important. The types of matter wasted in human settlements are: biodegradable waste, reusable waste, storm water runoff and non-degradable waste. The biodegradable waste can be considered as a source of nutrients that can go back to nature by bioremediation methods. Many non-degradable wastes can be recycled.

Landfilling has dominated solid waste management around the world. In the developed world, sanitary landfills have been the norm, while in the less developed world it is mostly land dumping. While the former method is more scientific and safe to some extent, the latter is dangerous. Landfill spaces are fast running out, and in

many densely populated countries domestic wastes are just dumped for lack of adequate land space for sanitary landfilling. Modern lifestyles only exacerbate problems; the 'throw away' culture brings in many new waste materials into the environment. A more biocentric viewpoint is long overdue, which emphasises a careful management technology. Most organic waste can eventually return to the land from where it originated.

In bioremediation technologies (sometimes known as microbiological engineering) the natural ability of certain organisms to degrade organic chemicals is used to contain contamination [Al-Daher *et al.* 2001]. The desired end results of the active bioremediation processes are CO_2, water and cell biomass; and the process is termed composting. Materials subject to aerobic biodegradation include complex aliphatic and aromatic compounds, as well as Poly-Aromatic Hydrocarbons (PAHs), chlorinated aliphatic hydrocarbons and chlorinated aromatics such as Polychlorinated Phenyls. Aerobic biodegradation happens in nature in the production of humus from naturally occurring biodegradable wastes.

The following definitions are used in this thesis [Shimp 1993]. A **compostable** material is *a material which undergoes physical, chemical, thermal and/or biological degradation in a MSW* (Mixed/Municipal Solid Waste) *composting facility such that it enters into and is physically indistinguishable from the finished compost and which ultimately mineralises (biodegrades to carbon dioxide, water and biomass as new microorganisms) at a rate like that of known comopstable materials in solid waste such as paper and yard waste.* A **compost compatible** material is *a material that disintegrates and becomes indistinguishable from the final*

compost, and is either biodegradable or inert in the environment. A **removable** material is *a material that can be removed (not to be composted) by existing technologies in MSW composting* (such as plastics, stones, glass etc.)

1.6 Conclusion

This thesis adopts a whole of waste approach to waste management for residences. The thesis argues that a small-scale, residential level system can be designed that will treat waste to reduce biohazards and produce useful by-products. The emphasis is on vermicomposting. A review of the fundamental process involved in waste treatment will be presented in the following chapters prior to presenting the design of the treatment system, test protocols and discussion of results.

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"It's a social and environmental crime, in my mind, to bury or burn organic waste. Composting should win every time over any other way of dealing with organic waste".

Dr. Paul Connett
Professor of Chemistry, St Lawrence University, NY, USA.
(Quoted from WMAA News, Autumn 2004, p8).

CHAPTER 2 WASTE AND WASTEWATER TREATMENT

2.1 Introduction

The issue of waste and wastewater treatment and reuse has been studied extensively worldwide and many technologies have been proposed. The type of technology that is appropriate is specific to the circumstances. Issues involved in assessing appropriate technology include the capacity of residential users to pay, availability of materials, skills, weather patterns and general climatic and geographical factors, aesthetic and societal constraints, population density, the ecological mind-set of the persons involved with the treatment system, the scientific and legal issues relating to the technology and finally, the significance of the need for the technology.

This chapter reviews technical options for waste and wastewater treatment and presents vermicomposting as a suitable technology for domestic waste management. It precedes a review of the chemistry, physics and biology of vermiculture technology. Chemical reactions are common to most treatment options and knowledge of these reactions is basic to understanding the physical and biological transformations. The emphasis in this thesis is on blackwater and solid waste management, with separate treatments suggested for greywater, as advocated elsewhere [Skjelhaugen 1999].

2.2 Review of Wastewater Treatment Options

Water reuse is gaining importance, not only amongst professionals but also amongst the general population. Potable reuse of treated greywater has been reported from Namibia, Pretoria and USA [Thomas 1997]. On the other hand, direct recycling of domestic blackwater in agriculture and aquaculture has been practiced in many countries with tremendous risk to human health [Pescod 1992; Edwards 1995; ATN 1997; Sophin 1999; REUTERS 2002].

In India, except the big-city-centres where space is limited, houses, small residential units, institutions and most commercial centres have separate plumbing for greywater and toilets. The blackwater goes to septic tanks and greywater goes to pits from where the water irrigates the plants through natural percolation into the ground. There appear to be no adverse health reports on this separate treatment. To be on the safe side, there is an argument that proper (or approved) treatment of the separate waste streams should be made mandatory.

The choice of technology that is appropriate for the particular implementation is important in terms of maintenance and cost. Some modern technologies, such as reverse osmosis, have significant cost implications and give rise to problems of implementation in developing economies. The emphasis in this review is on small-scale local systems appropriate to residential areas.

Near-potable standards have been reported for greywater recycled through biological processes in an experiment at Loughborough University [Surendran and Wheately 1998]. Hammes *et al.* (2000) reported on a 'mix-first-and-separate-later' approach

experiment, which produced very safe recycled water. The authors claim that by this method, more nutrients are made available from the combined household sewage by removing urine and faeces from greywater by *ecotechnological* methods. The different components of wastewater were treated according to their individual qualities. There are problems in treating combined blackwater and greywater effluent, and advantages in treating them as separate waste streams. In smaller systems it may be better to treat the blackwater to greywater quality and then treat all the greywater together.

Lodge *et.al.* (2000) report that the technology employed at the largest water recycling treatment plant in Europe, at the Millennium dome, involved a biological aerated filter (BAF) for greywater treatment, which removes suspended solids (SS) and carbonaceous organics with microorganisms. After treatment, the water from wash areas, rainwater from the roof, and groundwater is further treated through ultrafiltration and reverse osmosis. The 50-240 mg/l BOD of greywater is reduced to 1-15 mg/l and 48-124 mg/l of SS are reduced to 2-5 mg/l by BAF. The millennium project uses only greywater, and excludes blackwater (higher BOD and SS). Blackwater is discarded into the sewer [Lodge *et al.* 2000].

Jefferson *et.al.* reported the highest efficacy of treatment for membrane bioreactors (MBR), above the performance of membrane aerated bioreactors (MABR) and BAFs [Jefferson *et al.* 2000]. MBR proved to be very effective in stabilising influent water quality variations. Shin *et.al.* [Shin *et al.* 1998] experimented on a sequencing batch reactor (SBR) with microfiltration techniques for greywater reuse at an office

building in Japan. The effluent had 20 mg/l [4]SCOD, 5 mg/l BOD and 0.5 mg/l ammonia. The SBR was superior compared to other mentioned technologies (MBR, MABR, BAF etc) and the cyclic operation mode proved better than conventional activated sludge processes. SS concentration was one handicap and microfiltration reduced this to very low levels. SBR technology is good enough for applications such as gardening and toilet flushing, as per current standards [WHO 2003].

Many types of aquatic macrophytes have been used in domestic greywater treatment, traditionally in reed bed or pond systems. Submergent macrophytes such as *Schoenoplectus Validus* and *Triglochlin huegelii* were examined by Mars *et.al.* [Mars *et al.* 1999] in Western Australia. *T.huegelii* proved, in this test, very useful in removing nitrogen and phosphorous. The authors suggest lagoons, wetlands and constructed basins filled with plants like this for nutrient stripping. Though this can be cost effective and environmentally friendly, it needs space and the applicability of this technology in residential areas would not be attractive.

Anda *et.al* (1997) reviewed different technologies in greywater treatment currently under research in Western Australia. In amended soil filters, 90-mm diameter perforated HDPE pipes are used for subsurface irrigation in prepared ground where a thick vegetation of vegetables and herbs are grown. Aerobic biological activity and presence of earthworms are promoted. The ground is prepared with red mud, sand and a thick layer of wood chip mulch. System performance is currently being

[4] SCOD = Soluble Chemical Oxygen Demand, COD of the filtered effluent from which all particulate matter have been removed.

monitored [Anda *et al.* 1997]. Separately in sand filtration, greywater is filtered through two deep bed sand filters and then applied to an irrigation field.

In another study reported by Anda *et.al.* (1997), the combined effluent of treated blackwater and greywater was aerated to achieve secondary treatment standards, and then disinfected before irrigation of constructed wetlands. *Phragmites australis* was used as macrophyte for nutrient stripping. Emergent macrophytes and submergent macrophytes are used for better performance across various seasons. Details of the process or long-term performance data were not available [Anda *et al.* 1997].

The 'Aquarius' aerobic treatment unit is reported to remove nutrients to below 1 mg/l. The technology involves primary sedimentation and aerobic digestion, anoxic denitrification and chemical phosphorous removal, aerobic biological oxidation including nitrification in subsurface biofilter and denitrification in a submerged filter, secondary clarification and sludge recycling and finally chlorination. For treating greywater alone, the first stage can be avoided because of low SS levels. Treated water is used in toilet cisterns after disinfection [Anda *et al.* 1997]. Any excess effluent can be used in the garden.

Of all the above five technologies reported by Anda *et.al (*1997*),* aerobic treatment and irrigation is the most commended, due to the good nutrient removal and safety of aerobic treatment. Though nutrients are good for irrigation, these could be problematic when the treated greywater is to be used for other purposes such as non-potable residential use. The associated costs were not available from the paper, but the Aquarius technology may be best suited for places without much space such as

big cities with a high population and massive residential complexes (e.g. Singapore, Bombay and Tokyo).

For households without a garden/lawn/agriculture land, irrigation will not be useful. An alternative would be centralised collection and storage for irrigation, i.e., to collect treated greywater through pipes that lead to a location that needs to be irrigated. Constructed wetlands can be considered where adequate space is available. There are other uses for treated greywater, such as flushing toilets, car washing, construction works, fire hydrants etc.

Hammes *et. al* (2000) experimented with anaerobic digestion (AD) for treating biowastes with blackwater treatment at thermophilic conditions, with options of partial energy recovery as biogas containing methane (1 m^3 methane gives 35 MJ energy) and water reuse. Their report pointed out that between 70% and 90% of annual expenses are related to waste transport to centralised treatment plants. The authors suggested co-digestion (AD) of dry black waste (solid part of blackwater) with grey waste (biowaste) [Hammes *et al.* 2000]. Thermophilic anaerobic reactions are complex and odorous gases are generated. The technology is unlikely to be marketable for household use. The system is not totally accessible and accidental input of any material could disrupt anaerobic reactions by creating an organic shock load. Their technology requires that only dry toilets are used and this is not very acceptable amongst the wider population.

Dixon *et.al.* (1999b) demonstrated the water saving potential of a combination of wastewater reuse and rainwater harvesting. The basis of their analysis was data from

a small-scale study of domestic water appliance usage, from which cumulative frequency distributions were derived for each hour of the day and for occupancy. Their study concentrated on an urban housing environment.

2.2.1 Health aspects of wastewater treatment

Issues of environmental health demand that we utilise our resources wisely. Discharging effluent from centralised wastewater treatment facilities into rivers, lakes and oceans can be viewed as losing resources.

Health issues regarding residential wastewater reuse require careful analysis. The degree of exposure and physical conditions of the persons affect the chances of infection. Many reports speak of people engaged in illegal reuse of greywater, such as in Western Australia [Anda *et al.* 1997; Dixon *et al.* 1999a]. Public health authorities have to develop appropriate guidelines on water reuse for each area. Proper risk analysis is a must with reference to the particular area – the perception of risk can change dramatically depending on location and life-style.

While many technologies are available for wastewater treatment, they all need careful evaluation of their advantages and disadvantages. Some are costly, while others are useful in different scales.

2.3 Solid Waste Treatment options

The amount of solid wastes produced per capita, for all economies, is increasing [Ahmed and Ali 2003]. Lifestyle changes have resulted in an increase of per capita domestic waste production. It is accepted that careful reuse and recycling of solid wastes is the way forward for resource conservation and Integrated Solid Waste Management options should be adopted [Golueke *et al.* 1986; Beukering and Gupta 2000; Li 2003].

2.3.1 Solid Waste Treatment by Biological Methods

Organic Waste is readily biodegradable and includes green, putrescible and grease trap wastes, but does not include plastic or mineral oil products.. Putrescible Waste is waste that will decompose readily under microbial attack. It includes green waste and certain wastes arising from residential, commercial and industrial sources. Typical municipal waste streams can comprise from 30% to 60% of organic materials (i.e. green waste, food waste) [UNEP 1998].

There are several biological methods for the onsite treatment of organic municipal solid waste. The different methods of biological waste treatment are grouped as aerobic and anaerobic processes [Golueke *et al.* 1986; Haug 1993; D'souza 1999; Grover *et al.* 2000; Fyfe and Dharmappa 2001; Fraser-Quick 2002]. These are listed below and are briefly reviewed in the following paragraphs:

1. Aerobic microbial composting
2. Vermicomposting
3. Aerobic wet composting

4. Anaerobic digestion

2.3.1.1 Aerobic microbial composting

Aerobic composting is the controlled biological decomposition and pasteurisation of organic materials under aerobic conditions. Composting involves the action of mesophilic microorganisms followed by thermophilic microorganisms that thrive under increased (more than 50^{o}C) temperature conditions and if correctly managed, can destroy disease-causing organisms [Hogland and Marques 2000; Sidhu *et al.* 2001; Pattanaik *et al.* 2002; Vinnerås and Jönsson 2003]. Composting is the rapid and vigorous humification of organic matrices by a mixed population of exothermic microorganisms in a warm and moist, aerobic environment. Biodegradable organic matter is mineralised while CO_2, water and heat are liberated, and the residual organic components are stabilised mainly to humic acids. The development of the humic structure is a time-dependant process and the humic substances are formed in the early stages of humification [Hänninen *et al.* 2003]. These are heterogeneous natural polymers and have yellow to brown colour and are of high molecular weight and refractory properties. These are divided into humic acids, fulvic acids and humins.

Enclosed composting is an aerobic composting process that confines the composting mass within a building, container or vessel. There are a variety of methods that combine different vessels, aeration devices and turning mechanisms [Haug 1993]. By enclosing the waste, the atmosphere, moisture conditions and odours can be further controlled, which improves the rate of organic waste decomposition. The enclosed

nature of the technology allows for the input of potentially odorous waste such as: food waste; sewage sludge; and agricultural wastes.

Composting systems can be interventionary (windrows) or non-interventionary (static piles). In both, there are four indicators considered for process performance and product quality, namely, volatile solids, respiration rate, germination tests and pathogen indicators. Composting as an engineered process is not set up to fully decompose all degradable organic materials, but to degrade putrescibles that would otherwise cause odours by anaerobic degradation. Contrary to popular belief, aerobic composting releases a small amount of odorous gases even under favourable conditions. The released chemicals include ammonia, acetic/pyruvic acid and citric acids [Haug 1993], some of which are not objectionable.

The selection and design of the particular composting system depends on available materials. The controllable factors in composting are the design parameters of scientific interest: organic amendment, moisture level, C: N ratio, aeration, particle size, process temperature, ambient temperature, %recycled compost, retention time, mixing equipment, depth, reactor vessel size, %recycled air, turning frequency, type of process, pH moderator, curing time, initial moisture, inoculation and bulking agents [Hansen *et al.* 1992; Keener *et al.* 1992].

The controllable factors in composting are the method of composting, aeration rate, moisture content and substrate content [IFAS 2002]. Controlling any other factors affecting the smooth progress of composting operation, due to its biological nature, would be difficult.

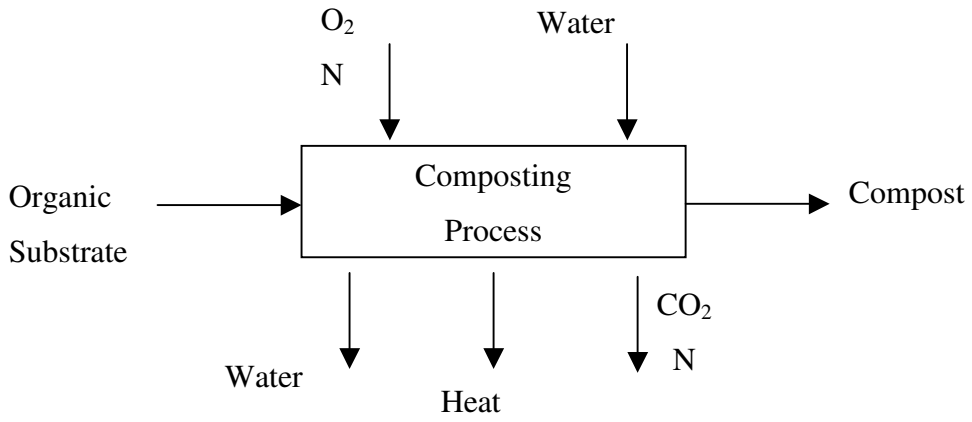

Figure 2.1 Process diagram of composting process.

During the conversion of the organic substrate into the stable material called compost, the major intakes are nitrogen, oxygen and water, with by-products as heat, water, nitrogen and carbon dioxide (Fig 2.1). The process itself is biological in nature, with actions from microbes, worms and other organisms. Aeration is very important because it provides oxygen for the organisms and forms the basis of the distinction between different methods of anaerobic and aerobic processes. Moisture content is at the same time a controllable input as well as an affected output. Substrate quantity and quality are the easiest controllable factors as the system operator can decide what waste materials go in the composting chamber.

The choice of the method of composting is based on the objective. If volume reduction and fertiliser production are the most important requirements, aerobic composting is selected. If the substrate has higher moisture levels (such as sludge or manure from livestock), or if biogas production is the primary aim, anaerobic digestion would be more appropriate. Aesthetic factors such as odour can be a deciding parameter, and in this regard, aerobic composting is preferred over

anaerobic methods for biological waste management in residential areas [Dragt *et al.* 1987; Baeten and Verstraete 1992; Miller 1992; Stentiford 1992; Hammes *et al.* 2000; Louhelainen *et al.* 2001; Shin *et al.* 2001].

There are many different technologies named after the origin of the process among windrows and static systems, such as Rutgers Strategy, Indore process or Camby process [Howard 1935; Finstein and Morris 1975; Stentiford 1986; Oorshot 2001], which are all large scale composting systems. Studies have been conducted on using composting technology for oil-contaminated soil beds in the Middle-East [Al-Daher *et al.* 2001]. The ability of microbes in disintegrating complex organic molecules has been the subject of further studies such as in treating biodegradable plastic [Narayan 1993; Richard *et al.* 1993; NASA 1997; WME 2002].

Vermicomposting, which is composting using worms, can be a faster alternative for organic waste treatment, with the added advantage of better quality fertiliser with nutrients in the slow-release form. Vermicomposting also adds valuable soil microbes into compost and digestive fluids of worms can also be beneficial.

2.3.1.2 Vermicomposting

Vermicomposting is the breakdown of organic material that, in contrast to microbial composting, involves the joint action of different species of earthworms and microorganisms and does not involve a thermophilic (i.e. high heat) stage. As the agents of turning, fragmentation and aeration, the worms consume organic wastes such as food waste, animal wastes and sewage sludge to produce a soil conditioner.

Traditionally, worms have been used to break down manure, which makes it an appropriate process for sewage sludge degradation [Darwin 1945; Dominguez *et al.* 1997; MWAC 2001]. Vermicomposting may only process organic waste of a suitable structure for worms and the optimum waste streams include some food wastes, sewage sludge, garden waste (leaves and grass) and manure. Studies have shown that vermiculture is an effective method of treating pathogen-rich waste materials [Eastman *et al.* 2001; van Zoest 2002] and domestic solid and liquid wastes [Taylor *et al.* 2003].

Treatment of wastewater by filtering through a vermicomposting mass has been tried and tested. Results of tests on the technology show this as a useful waste treatment option [Taylor and Clarke 1997; Taylor *et al.* 1998; Taylor *et al.* 2003]. Many pollutant levels were reduced by the technique such as oxygen demand and ammonium. The authors conclude that sufficient bed depth of the composting mass is a significant factor for the treatment.

Data from these tests were utilised in the development of a technology called biolytic filtration that treats both solid wastes and domestic wastewater through vermicomposting. Commercially developed by Dowmus Technologies Pty Ltd and promoted by Biolytix Australasia Ltd, this technology filtered domestic wastewater through a bed of kitchen waste and paper shreds undergoing the process of vermicomposting [Dowmus 2001; Biolytix 2004].

In biolytic filtration, wastewater is filtered through a bed of vermicomposting mass comprising of a humus filter matrix made up of vermicasts and undigested solid

waste material. The pollutants in the wastewater are trapped in this matrix and broken down by the action of diverse groups of organisms living in the matrix [Biolytix 2004]. It is argued that the pathogens in the waste are reduced by the action of higher microorganisms such as protozoa. This technology has found some applications worldwide and has been accepted as a productive waste treatment option [Darroll 2001; GENOA 2001; DEIR 2004; Greenhouse 2004]. While the Biolytix system is similar in concept to that presented in this thesis, it is designed for more developed economies and has several differences not only in scale but also in operation.

2.3.1.3 Aerobic wet composting

The waste material treated in normal microbial composting is mostly dry, as higher moisture content can reduce the interstitial space thus reducing air passage. This can lead to process failure, as aerobic microbes cannot survive in the absence of oxygen. In vermicomposting, higher humidity is tolerated/required as worms can survive humid environments and the burrows created by worms act as channels for air passage. A varied substrate mass can be treated by wet vermicomposting. Toilet facilities employing wet composting technology have been reported [DLG-NSW 1998; Boyden and Robilliard 2001; Ho 2001].

2.3.1.4 Anaerobic digestion

Anaerobic digestion is the break down of organic materials either occurring naturally or under controlled conditions in the absence of oxygen. The carbon content of the material is released as biogas (known as landfill gas in case of sanitary landfills),

containing methane, carbon dioxide and other gases. This technology is appropriate for the organic component of MSW if biogas retrieval is preferred [Kurup 2003]. Studies have reported on optimisation of the technology with thermal pre-treatment [Pratapchandran *et al.* 2003] and sequential batch systems [Mohee and Ramjeawon 2003]. Anaerobic digestion is suited to treat a mixed organic input stream, which may include: sewage sludge; pre-sorted agricultural waste and food waste [MWAC 2001]. The generation of odorous gases can act against the installation of anaerobic systems in populated areas.

2.3.2 Quantity and quality of compostable materials

The composition of MSW changes from season to season. In commercial composting processes, pre-treatment and mixing is necessary due to high volume of substrate. The amount of biodegradable waste from households depends on lifestyle and the number of people. Generally it includes the wastes from food preparation, garden waste, paper and blackwaste (the solid part of blackwater – nightsoil).

The quantity of human solid waste is affected by food habits that differ between places; for instance, Asians create much less than Africans, as the lowest and highest extremes, owing to the wide difference in food habits. It is estimated that 5 billion kilos of human excreta is produced daily worldwide [DLCME 2001].

The quality of the mixed domestic biodegradable waste is characterised by [Lindstorm 2000b]:

- Mix of nightsoil and household biowaste - unpredictable composition and quantity

- Very high BOD (3000mg/l), COD (more than 6000mg/l), nutrients, pathogens
- High moisture content
- Climatic changes affect quantities of ANS (Anthropogenic Nutrient Solutions)

The compostable part of domestic waste stream can be differentiated into several classes according to the organic content.

Class 1:

- Garden / landscaping material; Untreated timber
- Natural fibrous material and processed fibrous material

Class 2:

- Biosolids and manure
- Other natural/processed vegetable material

Class 3:

- Meat, fish and other fatty food items
- Fatty and oily sludge and materials such as de-watered grease-trap waste.

The higher the class of material, the more likely it is to cause environmental impacts if dumped outdoors [NSW 1996]. Each class of material has different degradability. Most of the putrescible domestic waste fall into the different classes, and can thus be treated by composting. Another classification of organic materials is based on the breakdown rate [Stentiford 1992]:

Group 1: Readily degradable: sugars, starches, glycogen, pectin, fatty acids and glycerol, lipids, fats and phospholipids, amino acids, nucleic acids and protein.

Group 2: Slower to degrade (degrades during maturation): Hemicellulose and cellulose, chitin, low molecular weight aromatics and aliphatic compounds.

Group 3: Usually resistant: Lignocellulose, Lignin.

2.3.3 Advantages of waste management by composting

Dry composting is practiced around the world for disposal of household biowastes. Many models of waterless composting toilets are available. Clivus Multrum is one company that has found a good market with their product [ClivusMultrum 2001]. But dry toilets are not widely acceptable due to the public being more used to the sound of the flushing water that gives an aesthetically appealing sensation of cleanliness.

Composting is a very effective method for treating wastes with high organic content. There are several advantages of composting such as a safe treatment option for high nutrient waste and the production of natural fertilizer as an end product. Aerobic composting is controlled and rapid while anaerobic composting is slow. Anaerobic process gives large quantities of odorous gases, which can be another source of energy, but composting of mixed domestic waste is not recommended in anaerobic form in residential areas for this same reason.

The process of composting has been used for many centuries around the world for different purposes, in different forms, with different technologies. But the basic principle and reactions have remained unchanged all these years, that of converting biodegradable waste materials into a product called compost which is the humus that is naturally produced in nature by very natural processes over time. The only difference between natural humus production and composting is that in latter, the

natural processes are intensified in a controlled environment, under careful monitoring. The major factors affecting composting can be grouped as chemical, physical, biological, engineering and environmental factors, and will be reviewed in later chapters.

2.4 Review of the Relevant Standards and Regulations

Regional/local health standards set by different national or state Environmental Protection Agencies/Authorities (EPAs) as well as international organizations such as World Health Organisation (WHO) will influence the design of any treatment system. There are many standards on drinking water. Standards and guidelines also exist relating to the handling of blackwater and other wastewater, solid wastes as well as products of different treatment processes such as compost. The following two sections discuss some relevant guidelines relating to wastewater treatment and vermicomposting.

2.4.1 Guidelines for Water Treatment and Testing

Though an indication of some level of faecal indicator bacteria cannot be taken as final pathogenic quality criteria, enumeration of *E.coli* as the most commonly found indicator organism in human excreta has been accepted by WHO (2003) guidelines. Colony counts (Colony Forming Units – CFU) have been accepted for routine monitoring of thermotolerant coliforms and *E.coli* [ADWG 1996; AS/NZS1546.1 1998].

Counts of less than 100 CFU/100ml for disinfected water supply and less than 500 CFU/100ml for un-disinfected supply have been prescribed. Tests for the presence of specific pathogenic organisms are appropriate for special investigations but are not recommended for routine monitoring of water supplies, due to the complexity of testing, associated cost, and unreliability of detection [ADWG 1996].

Total dissolved solids (TDS) values of more than 600mg/l has been mentioned in WHO guidelines as affecting the palatability of drinking water. A turbidity of less than 5NTU has been given to be acceptable for consumption, but turbidity less than 1 NTU is required for effective disinfection. Australian standards have prescribed less than 100 mg/l of nitrate and 0.5 mg/l for ammonia in drinking water for safe consumption [ADWG 1996].

There are differences between standards due to the basis of the calculations done in formulating the standards and guidelines. For example, the average body weight of a person is different between Australian and WHO drinking water guidelines [ADWG 1996; WHO 2003]. Generally, international standards have to take into account the existing conditions in developed as well as developing and poor countries whereas standards in specific countries need only to account for the specific conditions.

2.4.2 Guidelines for Vermicomposting – procedures and parameters

The third edition of Australian Standard 4454 [AS4454 2003] on composts, soil conditioners and mulches included vermicomposting. This standard does not apply to home composting end products for self-use, organic fertilizers, liquid organic wastes, liquid seaweed products, non-organic mulches, non-organic soils and soil

conditioners, non-compostable materials (plastics) and compost starters. Vermicasts are included subjected to some conditions, after consideration of comments from public discussion in 2002.

The Australian Standard mentions the best practice criteria for vermiculture systems and provides several quality assurance tests and methods and provides physical and chemical requirements for vermicastings along with other compost [AS 4454 2003, pp. 16-19; Appendix O]. Appendix L prescribes a method for determining the contamination level with larger particles, while appendix M prescribes a method for determination of plant propagules (seeds or roots) in the castings that have escaped the process. The best practice guidelines as prescribed in the appendix O of AS 4454 offer guidance for the preparation of raw waste materials for vermicomposting. The depth of the mass being vermicomposted, moisture content, temperature and oxygenation throughout the matrix and duration of the operation are important.

Due to the absence of pasteurising temperatures in vermicomposting, it is recommended that the raw ingredients be made free of plant pathogens and propagules by pre- or post- pasteurisation by microbial composting or steam injection. This could also reduce any risks of transmission of human pathogens, though well maintained vermicomposting systems are reportedly able to achieve adequate sanitation. Odour problems are generally minimal, except when system performance is inadequate in terms of highly degradable organic waste being added in excess. A homogeneous mix of feedstock is stressed as of paramount importance.

The minimum bed depth of mature vermicast, given as the initial bedding material for the worm population, is 0.3-0.4m. An optimum C: N of 20-25 is recommended for avoiding anaerobic conditions from low values (excess N is released at low C: N values), with pH of 5.5-8.5 and electrical conductivity less than 3 dS/m. Optimum moisture levels in bedding are within the range 30-70% while that in the active layer (raw waste) range 80-90%. Temperature of vermicomposting should be between 5 and 35^{o} C. An aerobic environment of not less than 10% free oxygen is required in the active layer. Worm biomass of 5-15kg/m^{2} is recommended. A minimum processing time of 6 weeks is recommended with an additional 4-6 weeks of maturation period after removal from the system [AS4454 2003].

2.5 Conclusions

Recycling of household waste and wastewater can be performed using biological methods. A low-cost technology would aim to have its processes as close as possible to the natural degradation processes. Aerobic vermicomposting is arguably a preferred method of waste management.

For the successful composting of any type of material, the physics, chemistry and biology of composting process as a whole need to be studied and monitoring parameters identified. The process of composting is composed of a number of intermediate factors. There is considerable interdependence among the factors. The most basic transformation reactions are chemical in nature; therefore the chemistry of composting, and as relevant to vermicomposting, is described next. The different factors are reviewed in the following chapters.

CHAPTER 3 THE CHEMISTRY OF COMPOSTING AND WASTEWATER TREATMENT

3.1 Introduction

This chapter on the chemistry of composting describes the basic chemical reactions of the material transformation and release the nutrients in soluble form. The reactions are affected by acidity or alkalinity, oxygen usage, the heavy metal cycle, nutrient cycles, trace elements that are needed for the converting microorganic community, contamination by harmful chemicals, concentrations of different ions, BOD and COD of the substrate constituents, mass balance of different elements, water content and several other factors. The major nutrient elements that are involved are N, P and C [Diaz *et al.* 1986; Epstein 1997; Sánchez-Monedero *et al.* 2001].

The parameters of interest in vermicomposting are pH, oxygen consumption, nutrients, BOD, COD and moisture. These control the quality of the end products, particularly in relation to the way plants will be able to utilise the compost. By keeping all the chemical elements at source and not releasing them into natural watercourses, pollution caused by the release of waste is reduced.

3.2 Chemical Quality Parameters

While trying to mimic the natural process of humification in composting, caution must be exercised not to shock the bio-chemical balance involved in the process. Generally, controlling the substrate composition effectively controls most chemical

actions. All matter that comes out of a composting process came into the process only through addition as substrate. The substrate undergoes different chemical reactions and gets transformed into other materials and energy. There are several well-recognized parameters that describe the chemistry of waste materials (Table 3.1).

Table 3.1 Chemical parameters of relevance to different types of waste

Solid Wastes	***Liquid Wastes***
Oxygen (aeration)	Oxygen (DO)
COD	BOD, COD
pH	Acidity/alkalinity (pH)
C: N ratio; Carbon cycle	Electrical conductivity (EC)
Nitrogen cycle (nitrogen content – nitrate, organic)	Nitrogen content – nitrate, ammonia
Phosphorous content (as phosphate)	Phosphorous content (as phosphate)

3.2.1 Chemical parameters in wet composting

A separate discussion on the chemical parameters of interest regarding solid waste and liquid waste is difficult in wet composting, as the solids and liquids are treated together yet chemical reactions may proceed differently in liquid – solid phases. The characteristics of one form of waste will have an effect on the other form of waste, such as a high pH in the liquid extractant of solids raising [AS4454 2003] the pH of the liquid waste. Most of the chemical parameters in the treatment system are common to both, with the exception of a few. C: N ratio and carbon cycle are of importance to only solid waste, while BOD and EC are of more relevance to liquid wastes.

Oxygen is a major factor controlling the composting process. For solid wastes, aeration and adequate supply of oxygen is important; for liquid wastes, dissolved

oxygen level is important. Composting, being an aerobic process, demands a continuous and good supply of oxygen for the microbes and other organisms such as worms, beetles and nematodes. There are always anaerobic pockets within the composting mass at the micro-level [Haug 1993]. Any deficiency in oxygen levels can easily trigger the dormant anaerobic community to reactivate and start processes on their own. Anaerobic reactions can cause an imbalance in the whole system and stir up malodorous gases. The very reason for preferring aerobic process to anaerobic process is easy operation and avoidance of such odours [de Bertoldi *et al.* 1988; Homans and Fischer 1989; Elvidge and Blitz 1992; Walker 1992; Oorshot 2001].

The pH value indicates the progress of reactions within the compost pile. The beneficial bacteria need a pH of 6.5 – 7.5 [Haddon 1993]. Authors such as Haug (1993) have shown the significance of pH. The pH indicates the stability and usability of compost and has particular relevance in the nutrient cycle analyses. It has been found that materials of pH 3-11 can be composted [de Bertoldi *et al.* 1983], though this range seems unrealistic for vermicomposting. Worms are not able to withstand such wide variations in pH [Jensen 1998; Jamieson 2000; Jayasekara *et al.* 2001].

The Biochemical/Biological Oxygen Demand at the end of a 5-day period (BOD_5) has been of importance in wastewater treatment as a measure of the level of contamination and potential to undergo reactions. BOD is the quantity of oxygen consumed for biological activity within the substrate – it gives a measure of respiratory consumption of oxygen. BOD could be present in wastewaters as soluble

BOD and colloidal BOD, the latter being closely related to the suspended solids as represented below [Eckenfelder 1991].

$$BOD_{total} = BOD_{soluble} + f'.SS \quad \ldots 3.1$$

Where BOD_{total} is the total BOD value, $BOD_{soluble}$ is soluble BOD, SS is suspended solids and *f'* is a coefficient related to influent waste characteristics depending on the content of SS.

On the other hand, a closely related parameter, Chemical Oxygen Demand (COD) measures the equivalent oxygen demand for the complete breakdown of organics by oxidative chemicals – it gives a measure of the ultimate oxygen demand by biodegradable and non-biodegradable factors. COD is related to the energy released during decomposition of waste. For every gram of COD removed in composting, 14.65 kJ energy is released as heat [Haug 1993]. For comparision, it has been reported that theoretical methane production from conversion of COD will be 340 L methane / kg COD in anaerobic digestion [Hammes *et al.* 2000].

Electrical conductivity (EC) in a substrate is caused by free ions that cause transfer of electrons. Conductivity or conductance of the wastewater sample is of more importance than that of the solid substrate. EC is closely related to another parameter, Total Dissolved Solids (TDS), which in a sense is a measure of the chemicals in solution. TDS in liquid waste can increase during mixed composting, due to disintegration of solid matter. Certain dissolved solids and free ions present in water can impart it strong colour, taste and odour [Clesceri 1999].

Nitrogen and Phosphorous contents appear as part of TDS, and are of importance for wastewater as well as compost quality. Both N and P are very important plant nutrients [Lindstorm 2000b; IMA-KTH 2001]. If left untreated, these elements in wastewater as well as solid waste can find their way into natural waterways and cause pollution. If captured in a useful product such as compost they can be beneficially utilised. Residential waste streams usually contain high level of nitrogen especially in blackwater, and high levels of phosphorous in greywater. Hammes *et.al.* (2000) reported that 75% of N and 50% of P in household wastewater comes from human urine and the combined ANS (urine and toilet effluents) account for more than 55% of COD and most pathogens in it. Co-composting with solid wastes can be a possible way to arrest them in a solid matrix.

The optimum C: N ratio for composting can be achieved by observing a correct mix of plant and animal product in the substrate. There are high C: N substances such as leaves (60:1), paper (170:1) and straw (100:1); high N or low C: N substances such as food wastes (15:1), fowl manure (7:1) and cow manure (12:1) as well as good mixes such as lawn clippings (20:1), weeds (19:1) and sea weed (25:1). A careful mix to reach a C: N ratio of 25:1 of plant to animal matter gives the optimum C: N ratio [Haddon 1993]. C: N ratios of certain compost-related materials are: micro-organisms (9-12), raw sewage sludge (7-12), activated sludge (6-8), cow manure (17-19), organic MSW (26-45), maize residue (80-90), wheat straw (120-150) and fresh sawdust (500-520) [de Bertoldi *et al.* 1983]. A detailed table of C: N ratios of common materials is given in Appendix V.

Haug (1993, p.248) has argued that the optimum C: N ratio is 30, based on theoretical analysis of cell synthesis for an average cell formulation of $C_5H_7O_2N$ with the reaction given as:

$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + \text{energy}$ ..3.2

But this reaction is governed by the energy provided by the cellulosic substrate for the microbe and this can be represented as:

$X\ (C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + \text{energy})$ ..3.3

$5CO_2 + 2H_2O + NH_3 + \text{energy} \rightarrow C_5H_7O_2N + 5O_2$ ..3.4

here, ammonia is the source of cell N.

The maximum yield of cells is limited by thermodynamics to 0.4 cells/g glucose. With an assumed net yield (yield coefficient) of 0.1 cell/g glucose, the moles of energy reaction required per mole of synthesis is calculated as

$$1/(X(180)) = 0.1/113$$

where 180 is the molecular weight of glucose and 113 is that the cell formulation.

This gives X = 6.3 or equivalent to 6 moles/mol.

Therefore the combined energy reaction of 3.2 and 3.3 is given as

$6\ C_6H_{12}O_6 + 31O_2 + NH_3 \rightarrow C_5H_7O_2N + 31CO_2 + 34H_2O$ ..3.5

Here, 36 mol of C is used for each 1 mol of N. This gives the C: N ratio as 36(12)/1(14) = 30.9.

For higher cell yield coefficient, the ratio falls below this value [Haug 1993]. The analysis also indicates that a lower C: N could trigger rapid cell growth, of course within limits of nutrient availability.

Nilsson *et.al.* (2000) studied the recirculation of plant nutrients, in the biologically degradable fraction of household waste. They found natural products such as fatty acids, fatty acid esters, *n*-alkanes, aliphatic alcohols etc constituted the major organic components in the waste samples. These organic fractions and their chemical derivatives cause the natural degradation of putrescible waste [Nilsson *et al.* 2000]. Mixing human urine with composting materials can change the chemistry of the composting matrix by virtue of the components of urine and its difference with compost (Table 3.2).

Table 3.2: Characteristics of human urine

Parameter	***Per capita value***
Flow	1.25 l/day
pH	6.3 ± 0.5
COD	15 g/day or 12000 mg/l
Nitrogen	11.5 g/day or 9200 mg/l
Urea-N	9.6 g/day or 7700 mg/l
Total P	1.2 g/day or 1000 mg/l
Total S	1.3 g/day or 1000 mg/l (100% daily intake)
SO_4^{2-}	1.2 g/day
Na^+	5.2 g/day or 4200 mg/l (>95% daily intake)
K^+	2.7 g/day or 2200 mg/l (80-90% daily intake)
Cl^-	4.8 g/day or 3800 mg/l (100% daily intake)
Mg^{2+}	120 mg/day (up to 50% daily intake)
Ca^{2+}	210 mg/day (30% daily intake)

Source: [Larsen and Gujer 1996]

Human urine and faeces contain valuable nutrients including nitrogen, phosphorus and potassium. Urine possesses the majority of nutrients, compared to faecal matter, containing approximately 80% of the nitrogen, 55% of the phosphorus and 60% of the potassium found in human excreta and available for reuse [Vinnerås and Jönsson 2003]. Many studies have been conducted on methods to remove nitrogen from residential wastewater [Buchanan *et al.* 1988; Shin *et al.* 1998; Iglesias-Jiménez

2001; Sánchez-Monedero *et al.* 2001; Vinnerås and Jönsson 2003]. The levels of ammonia and nitrates are usually measured to identify nitrogen levels in waste and wastewater treatment and nitrogen cycle usually involves cycles of nitrification and denitrification, which refer to oxidation and reduction of N in the waste. The levels of total P and orthophosphates (reactive P) give a measure of the relevant phosphorous content in the sample [Clesceri 1999].

Odour is a major aesthetic issue concerned with biodegradation of waste and is closely related to BOD. The higher the BOD, the greater are the chances of odour generation. The compounds that cause odours, their nature, production of volatile fatty acids (VFAs), odour thresholds and sensing of odour are issues to be dealt with during composting. The best measuring device for odour is the human nose. Weakly ventilated aerobic systems including passively aerated composting masses often exhibit significant anaerobic metabolitic pockets generating H_2S & CH_4. The odorous gases are H_2S, dimethyl tri-sulphide, carbon disulphide, dimethyl sulphide, dimethyl disulphide, benzothiazole, methanethiol, carbon oxysulphide, limonene and alphapinene as well as ammonia. Composting broiler chicken manure released 4.47kg ammonia per wet tonne (42.6% moisture). The higher the C: N, the lower the amount of ammonia [Homans and Fischer 1989; Haug 1993; Hoitink and Keener 1993].

Wiles *et.al.* (2001) examined composting of swine waste amended with sawdust. The major malodourous compounds in livestock manure were identified as volatile fatty acids (VFAs) including acetic, propionic, isobutyric, isovaleric and valeric acids as

well as aromatic compounds including phenol, p-cresol, indole and skatole. Most of these compounds are produced by anaerobic processes.

Ammonia is produced aerobically and anaerobically. Due to its highly volatile nature, ammonia is usually considered problematic in on-site systems. The mainly offensive gaseous emissions thus comprise mostly from VFAs. Wiles *et. al.* (2001) suggest oxygen unavailability is the main cause of VFA persistence within the system. Good aeration through the decomposing waste decomposes VFAs rapidly. Aeration eliminates production of methane and H_2S as well as reduces ammonia. It is reported that in small-scale systems, availability of oxygen affects degradation of malodorous compounds, but data are lacking for large-scale systems [Wiles *et al.* 2001].

Table 3.3: Chemical Compositions for Organic Compostable Waste Materials

Waste Component	***Chemical composition***
Carbohydrate	$(C_6H_{10}O_5)x$
Protein	$C_{16}H_{24}O_5N_4$
Fat and Oil	$C_{50}H_{90}O_6$
Sludge – Primary Sludge – Secondary	$C_{22}H_{39}O_{10}N$ $C_{10}H_{19}O_3N$
General Mixed Refuse (total organic fraction)	$C_{64}H_{104}O_{37}N$; $C_{99}H_{148}O_{59}N$
Wood	$C_{295}H_{420}O_{186}N$
Grass	$C_{23}H_{38}O_{17}N$
Garbage	$C_{16}H_{27}O_8N$
Food Wastes	$C_{18}H_{26}O_{10}N$
Mixed Paper	$C_{266}H_{434}O_{210}N$
Yard Waste	$C_{27}H_{38}O_{16}N$
Bacteria (providing nutrition to worms)	$C_5H_7O_2N$
Fungi	$C_{10}H_{17}O_6N$

Adopted from Haug (1993) p262.

Miller (1992) has reported that during composting of plant materials, phenol and phenolics can be found as water extracts at concentration 8mmols/100gm compost.

High-N manures and other wastes should be added to low N vegetative material, such as sludge to wood chips, cow manures to wood bark, poultry manure to straw or hay. S is contained in many biological compounds. Most animal manures have 0.25-0.30% S, while poultry manure contains 0.22-0.83% S. Production of ammonia is the major loss of N, due to de-amination of proteins and decomposition of other nitrogenous organics and urea. Poultry manure contains 25% protein with 2.3-6% N [Miller 1992]. Table 3.3 gives general chemical compositions for organic waste materials for their major component elements.

3.3 Nitrogen Cycle

Nitrogen is the most important element in organic waste decomposition, within a composting mass as well as after the composting process is finished. It is very important in controlling the rate of decomposition of organic matter, as micro-organisms that decompose the organic matter cannot multiply unless enough N is assimilated by them. Many organisms depend on NO_3^- as a source of N and high temperature have been found to be strongly inhibitive towards nitrification [de Bertoldi *et al.* 1988]. Besides, less nitrification can lead to ammonia build-up that is toxic to micro-organisms as well as higher organisms that take part in the natural degradation of organic matter [Finstein and Morris 1975; Walker 1991, 1992; Louhelainen *et al.* 2001].

Nitrogen-cycle analysis is important also because the C: N ratio is one of the factors that decide the progress of the process. An average 25-30 range of C: N ratio has been suggested by researchers for the composting to progress at optimal rate, given the other factors are favourable [Finstein and Morris 1975; de Bertoldi *et al.* 1983;

Eggen and Vethe 2001; Envirocycle 2002; ROU 2002b]. No particular tests have been prescribed or tried for the measurement of the C: N ratio other than by calculation based on the substrate components. A ratio of total organic carbon (TOC) and total nitrogen (TN) is acceptable. Studies have shown that estimation of mineralizable N have been highly unreliable [Van Kessel *et al.* 1999].

Most of the N found in a composting mixture is organic, principally as part of the structure of proteins and simple peptides. A small part of this N is mineralised to ammonia by ammonification reactions resulting from the microbial activity, which then is either dissolved and immobilised by the microbes or it is volatilised at high temperatures and at pH higher than 7.5 [Eggen and Vethe 2001; Sánchez-Monedero *et al.* 2001]. The latter happens mostly in static systems perhaps due to temperature build-up. Ammonium may also be transformed into nitrate by the two different species of nitrifying bacteria when the temperatures are below 40 ^{0}C and aeration is adequate. Lack of good aeration causes bacteria to use nitrate as oxygen source thereby causing denitrification. The main reactions can be represented as follows:

Nitrifying *Nitrosomonas* bacteria:

$$2NH_4^+ + 3O_2 \rightarrow 2NO_2^- + 4H^+ + 2H_2O \qquad \ldots 3.6$$

Nitrifying *Nitrobacter* bacteria:

$$2NO_2^- + O_2 \rightarrow 2NO_3^- \qquad \ldots 3.7$$

During the organic decomposition of putrescible wastes, ammonia can be released which can be harmful for the composting organisms. But nitrifying bacteria converts this ammonia into nitrates as per the following equation:

$$NH_3 + 2O_2 \rightarrow NO_3^- + H_2O + H^+ \qquad \ldots 3.8$$

Thus, during nitrification, pH is lowered by hydrogen ions released from ammonium. Sánchez-Monedero *et.al.* (2001) have further reported that higher lignocelluloses in the composting substrate gave lower N-losses compared with mixtures of only MSW with 40% of initial N-losses. This could be due to lack of nutrients in the former [Haug 1993]. The value of pH was seen to be directly related to nitrification and nitrate-N production also increases conductivity in the substrate. Increase in electrical conductivity is a direct consequence of the increased concentration of nutrients, such as nitrate, and therefore could be beneficial for use of the compost in agriculture [Lionello and Fransesco 1989].

The ratio between inorganic forms of N has been used as a criterion for assessing compost maturity. More nitrates than ammonium indicate that the process had adequate aeration. Nilsson *et.al.* (2000) have given a value of 0.02 ammonia/nitrate ratio for stability. High concentration of ammonium in compost indicates instability and it should not exceed 0.04% in mature compost. Presence of nitrites could indicate lack of oxygen or anaerobic conditions [Nappi *et al.* 1989; Haug 1993; Sánchez-Monedero *et al.* 2001].

The progress of N-cycle is not very different in vermicomposting [Dominguez *et al.* 1997]. Denitrification and nitrification occur in vermicomposting similar to microbial composting. Excess N can cause ammonia, which is toxic to worms as well, and lack of N can cause very slow processing of wastes as N-availability is essential for worms for growth and reproduction.

3.4 Carbon Cycle

Another very important chemical parameter in composting is carbon, the other element deciding the C: N ratio. Carbon forms the base of life whereas nitrogen is utilised for growth. The basic C-cycle can be represented as below [Narayan 1993]:

$$C_{substrate} + O_2 \text{ --> } C_{CO2} + C_{biomass/compost} + H_2O + \text{Heat} \qquad \ldots 3.9$$

$$\text{where } C_{biomass/compost} = C_{cellmass} + C_{humic\ material}\ .$$

"Organic C (is found in) *different reservoirs in nature, such as atmosphere, plant and animal (including human) substrates, soil and micro/macro organisms. C in the form of atmospheric CO_2 is taken up by plants and reduced to carbohydrates (primarily sucrose and starch) by photosynthesis. The C in plants is redistributed into herbivorous animals and then into carnivorous animals as secondary recycling of C. All these naturally occurring C-based materials such as plants, trees and all other living creatures are biodegradable and ultimately result in the formation of dead organic matter, which is then decomposed by soil microorganisms in a reversal of the photosynthesis process. Oxygen is employed as the electron acceptor, and decomposing materials provide the required C & N for the microorganisms. A portion of the waste material is used to create new cell mass and the rest is converted into CO_2 & H_2O. Lignin degradation and microbial synthesis produce secondary phenolic components, which polymerise along with protein degradation products resulting in humus. This humic material is a slow degradation material that releases stable forms of C and N into the environment that can be used by the various organisms, thus completing the cycle"* [Narayan 1993].

Simple C-compounds such as soluble sugars, organic acids etc are easily metabolised and mineralised by a heterotrophic and heterogeneous microflora. This activity and exothermic processes increase the temperature in the composting mass. This has a strong selective effect in favour of a few aerobic sporigenous (spore forming) thermophilic organisms, thereby proceeding into higher temperatures. Fungi and actinomycetes attack the natural long chain polymers. Carbon accounts for approximately 50% of dry body mass and is necessary to synthesize a variety of organic molecules for cell formation [de Bertoldi *et al.*; Haug 1993]. Heterotrophs use carbon available in the form of organic molecules, while autotrophs utilise carbon in CO_2. It is the organic or inorganic oxidation-reduction reactions of C that release the energy required for organisms to develop, other than light.

Organic matter is not solely carbon or solely nitrogen. All live organic matter has some of both elements, in varying proportions. After death, the ratio of carbon to nitrogen increases over time [Tynes 2000b]. An increase in C in the substrate can happen if dry matter is in excess, such as dry leaves, paper and cardboard [Finstein and Morris 1975]. The C: N ratio achieves the status of most important controllable parameter in regards to composting. Studies have shown that there occurs a declining relationship between the initial potential rate of C mineralization and the C: N ratio at C: N ratios less than 15. Above C: N ratios of 15, the initial potential rate of C mineralization is low and non-variable [Van Kessel *et al.* 1999].

The chemistry of vermicomposting differs only slightly from that of microbial composting. Vermicomposting is still a growing and new area of research and not much data is available. In vermicomposting, the natural degradation of materials

occur rather similar to microbial composting, but the rate or speed of degradation is facilitated by actions of worms as the partly degraded substrate passes through the tunnel-like body of worms and further degradation occurs [Morgan 1988; Jamieson 2000, 2001].

The worm castings (worm excreta) from vermicomposting contain plant nutrients encased in mucus membranes, which are secreted by the earthworms. These dissolve slowly rather than allowing immediate nutrient leaching. Vermicompost includes worm castings, some earthworm coccoons, inert materials such as sand and rocks, fibrous and woody material and some undigested waste material that continues to be decomposed by the indigenous bacteria [Bogdanov 2001; Fraser-Quick 2002].

Nutrient cycling and removal progresses are similar to microbial composting, but COD removal rates differ and the pH requirements of vermicomposting are also changed [Appelhof 1988; Aston 1988; Dominguez *et al.* 1997; DNR 2001]. The degrading complex chain compounds of a vermicomposting matrix also will be different from that of a microbial composting mass, due to the extra fluids secreted by worms. Reaction rates are different due to changed physical conditions such as aeration, moisture content, particle sizes etc.

3.5 Conclusions

An understanding of the chemical reactions occurring in a composting system is important in understanding the physical transformations in the waste and biological synthesis processes as well as for its design and operation. The chemistry of wet composting involves the transformations of matter in the solid as well as liquid

phases. It is difficult to analyse the two forms of matter separately, because of the effects each form of waste has on the other. The C and N cycles are the most important in composting and vermicomposting. But these processes are not only a chemical process. In the following chapter the physics of composting will be reviewed.

CHAPTER 4 THE PHYSICS OF COMPOSTING

4.1 Introduction

The physics of composting involves thermodynamics, moisture content, fluid flow, gas detection, particle size reduction and volume reduction. The different parameters can be grouped as *controlled/controllable* and *affected* parameters. The main objectives of composting putrescible waste, from a physical viewpoint, are volume reduction and material conversion. In vermicomposting, volume reduction is achieved by size reduction of the substrate particles by the action of microbes, worms and other insects. Odour is a possible side effect of material conversion, which is only a symptom of probable process failure. This chapter discusses the different physical factors of importance and their management in composting.

4.2 The Controlled/Controllable Physical Parameters

4.2.1 Aeration

The methods of aeration vary depending on the type of technology used in composting. Forced-draft (positive pressure) or vacuum-induced (induced draft – negative pressure) aeration are the two main types of aeration techniques used in open or closed systems composting [Epstein 1997]. In windrows, the air is pumped through pipes situated within the matrix. In tower systems (Vertical Composting Units – VCUs), air can be pumped up against the flow of materials. In other enclosed systems, air is pumped through the degrading matrix as forced ventilation is the only method that can aerate the mass properly. Pumping gases through the material has

been used in air pollution control, taking advantage of the absorbent powers of compost for certain gaseous molecules. Forced air pumping can also be used to control odour in the composting process [Pomeroy 1982; Ottengraf *et al.* 1986; Van Langenhove *et al.* 1986; Dragt *et al.* 1987; Bohn and Bohn 1988; Van Lith 1989; Van Durme *et al.* 1992; Dunson 1993; Brennan *et al.* 1996].

The method of aeration is the most energy-demanding factor in composting. An induced-draft (ID) or negative pressure fan uses forward-curved blades and draws air out of a system creating a negative pressure or vacuum, while a forced-draft (FD) or positive pressure fan uses backward-curved blades and pressurizes the system by blowing or forcing air into it [Goyal 1983]. For the same blade-tip velocity, the ID-fan creates a higher air velocity than the FD-fan, making the former ideal for handling large volumes of air in low-resistance systems. Disadvantages for an ID fan include higher levels of noise and dust accumulation on the blade causing an imbalance in the motor [Lipták 1995].

Finstein (1980) observed that induced aeration did not avert the problems of high temperature build-up, but forced aeration achieved this objective. He suggested that forced aeration also allowed better control of the process and induced evaporative cooling in the most highly insulated part of the composting matrix. Heat and moisture are transferred towards the outer edges and the process enhances the convective updraft set in motion by the temperature differential between the pile and the ambient air. Vacuum-induced aeration concentrates heat in the interior. Moreover, ID fans need more energy than an FD fan to create the same pressure change. It has been shown that at a constant speed, an ID fan would require 1.37

times more power than an FD fan to achieve the same level of aeration. The power requirement rises sharply as the static pressure decreases after the peak pressure has been reached and as the capacity increases [Goyal 1983].

As discussed in chapter 3, nitrification of ammonia is a major factor in completion and stability of a composting matrix because stabilisation of nitrogen is a primary index of compost stability. Most of the air required in a composting mass is for organic decomposition of the fresh substrate that is rich in nitrogen. Ammonia is released as a result of organic decomposition and is toxic to composting organisms. Ammonia should be further oxidised into nitrates, and lack of oxygen can disrupt this step. It can be found in the literature that properly aerated compost can absorb and oxidise ammonia and other toxic gases as well, such as hydrogen disulphide or sulphur dioxide [Furusawa *et al.* 1984; Dragt *et al.* 1987; Dunson 1993; Eggen and Vethe 2001]. Rate of aeration plays a major part here, and is thus the most important parameter in composting operation.

Optimisation of large composting systems for their automatic aeration rate has been a significant topic of research. Automatic oxygen feedback control has been successfully tested [de Bertoldi *et al.* 1988]. The exhaust air quality in terms of oxygen and process gases are sensed with chemical sensors and intake of air controlled adequately. Temperature can also be used as an indicator of process status and used in controlling air intake, as tested in Rutgers composting strategy [Finstein 1980; Finstein *et al.* 1989]. This was achieved by controlling the air flow into the system with a solenoid valve that was opened or closed by a thermostat [Schulze 1962]. More modern and accurate Programmable Logic Controllers can also be used

[Lipták 1995]. Such automatic control can be incorporated into domestic or small scale composting systems, depending on the aeration demands.

Haug (1993) has named the different aeration demands in a composting system as Stoichiometric demand (air demand for organic decomposition), drying demand (for moisture removal) and heat-removal demand. In microbial composting, temperature can reach formidably high levels if left uncontrolled and this can lead to drying-out of the composting mass, microbial and worm death and thus process failure. In microbial composting, the stoichiometric aeration demand can be calculated based on the chemical reaction formulae and chemical compositions of various organic components. In vermicomposting, this is unnecessary due to various reasons, such as high moisture content allowed, better aeration channels created when worms travel within the degrading matrix and faster decomposition. The aeration demand for heat removal is avoided because high temperature are never met in vermicomposting [Phillips 1988; Finstein 1992; Dominguez *et al.* 1997; Dowdle and Dowdle 2002; Hendrix and Bohlen 2002; ROU 2002b].

In wet substrates such as blackwater composted with putrescible household waste, calculations need to include the biochemical and chemical oxygen demands (BOD and COD, respectively) of the dry and wet parts of the feed substrate. Various studies have reported on the aeration demands of microbial composting, but not many reports could be found particularly on vermicomposting on aeration demand calculations. Aeration demands could be calculated based on the dry weight of feed and the fact that oxygen comprises 23.2% by weight of air [Haug 1993]. It is recommended to have a minimum of 25 L/hr/kg of volatile solids aeration rate

[Mears *et al.* 1975; Kaneko and Fujita 1989; Miller 1992]. Too much air could also be detrimental to decomposition due to over-cooling and dehydration of the matrix. In microbial composting, it is recommended that during composting the interstitial oxygen should at least be 10% [Karinda 2003].

Adequate oxygen supply ensures the aerobic processes progress smoothly, the aerobic bacteria and other organisms get enough oxygen for respiration; any odorous gases are removed in time. Temperature is controlled through heat removal. Careful aeration also takes care of moisture content, controls heat removal rate through moisture removal with gases from the mass [Kaneko and Fujita 1989]. In vermicomposting, lack of adequate air can cause worm fatality or worm migration and thus process failure [Phillips 1988; Finstein 1992; Dominguez *et al.* 1997; Dowdle and Dowdle 2002; Hendrix and Bohlen 2002; ROU 2002b].

4.2.2 Moisture Content

Moisture content is at the same time a controlled parameter as well as an affected parameter because aeration affects the moisture removal rate in a composting mass. Water can be added intentionally into a composting system or unintentionally as water contained in the waste substrate or released due to certain chemical transformations. Water droplets filling the interstitial spaces in the compost is important, as it controls the quantity of water for the composting organisms as well as provides heat removal [Finstein 1980; Aston 1988; Keener *et al.* 1992; REMADE 2000; IFAS 2002].

A good composting process needs an average of 60-65% moisture content (by weight), and this should be ensured at all times. Microbial composting cannot proceed with less than 20% moisture due to lack of adequate humidity to support growth. With more than 70% moisture the compost can go anaerobic and create odour problems [SRSWS 1996; Epstein 1997]. But with vermicomposting, moisture levels as high as 90% can be tolerated without the fear of going anaerobic [ROU 2001, 2002a]. This is because the worms, as they burrow through the compost, create air channels within the substrate that allow air to get to the innermost parts of the matrix. Moreover, worms require more humidity (60-90% moisture level) as a moist environment is one in which they can proliferate [Phillips 1988; Jensen 1998; Jamieson 2000; Dowdle and Dowdle 2002].

Moisture removal rate should be incorporated into the design process, taking into account the required moisture level, expected quantity of water added and the type of substrate being composted. Aeration rate and leachate/filtrate removal mechanism could be the tools for the purpose. In treating high water content materials such as in co-composting of blackwater with solid wastes, the effluent collection/removal mechanism has to avoid development of anaerobic conditions at the bottom layer of the matrix. Modern monitoring instruments are available for continuous measurement of moisture level in biological treatment systems [Gawande *et al.* 2003].

In biological treatment of solid-liquid waste mix, the conversion reactions could be taking place at the solid-phase or liquid-phase depending on the humidity level. Literature could be cited on studies of both types of material conversion reactions in

landfills and digesters [Martin 2003], but data is lacking in the subject of vermicomposting.

4.2.3 Substrate Composition

The materials put into the biological treatment system should be suitable for the particular method of treatment. As discussed in Chapter 2, the class of the different compostable materials is important in vermicomposting, as certain materials are disliked by worms and microbial decomposition alone could create odour problems at times. Addition of bulking materials for creating better interstitial spaces is also important in vermicomposting as well as microbial composting. Such materials help avoid the risk of creating numerous anaerobic pockets [Miner *et al.* 2001] and thus the production of ammonia and other odorous gases. Based on literature, microbial composting seems more suitable for treating a wide variety of materials including non-biological wastes [Al-Daher *et al.* 2001; Vitello 2001]. However, for the purpose of waste management in residential areas, the materials are largely organic in nature and vermicomposting is highly appropriate [LCC 2002].

Typical municipal waste streams can comprise from 30-60% of organic materials [MWAC 2001]. A random sample of domestic biological waste contains kitchen waste (including non-vegetarian food items), fruit peels, acidic and basic food items (such as oranges, milk products and onions), dry garden waste (high C: N ratio), fresh leaves and grass cuttings (low C: N ratio), paper shreds and cardboard pieces. The quantity and quality of these materials changes depending on the geographical locality – whether urban or rural, developed country or developing country - and the lifestyle of the individual home. In addition, there are seasonal and even daily

variations in the waste stream, which impacts on substrate composition [Finstein 1992; Hogland and Marques 2000; Bernache 2003; Buenrostro and Bocco 2003; Ambulkar and Shekdar 2004].

Table 4.1 Composition of MSW (*Approx. % by weight*) [Finstein 1992; Jain 1994].

Type of material	***USA***	***India (Urban)***
Paper and paperboard	36	4
Yard waste (dry and fresh)	20	60
Food waste/kitchen waste	9	
Metals and metal parts	9	0.45
Glass (bottles and other)	8	0.32
Plastics	7	1.3
Rubber and leather	3	
Textile and wood	6	9.51
Misc. organics (bones, ash etc.)	2	21
Other miscellaneous	1	3.5

Based on the average statistic from a decade ago (Table 4.1), the average compostable percentage of MSW in USA would be 32%, assuming the entire paper and paperboard content was being recycled, whereas in India it amounts to at least 80%. A typical waste stream from a rural area in a developing country can contain more compostable materials. The reported percentage quantities have not changed much recently [D'souza 1999; Buenrostro and Bocco 2003].

Particle size is an important criterion in biological treatment of waste for many reasons. The interstitial spaces or porosity is determined by the size of individual particles in a composting matrix. The larger the particles, the slower the degradation due to the smaller surface area to mass ratio [Haug 1993]. The literature shows that the initial particle size of the substrate is an important factor that affects the rate of

decomposition. Mears *et.al.* (1975) state that a 3.1cm average particle size is optimum when using a rotating drum composter with a mixture of plant residue, leaves and paper. But different substrate mixes in a household composting unit would not allow such generalisations. The particle size changes during composting follow a logarithmic normal distribution. The reported final particle size of composted mixture of swine waste and MSW is 3 times larger than compost from swine waste alone or combined with straw, and it has been shown that particle size is a clear indication of the stage of composting if the mixture of substrates is known [Mears *et al.* 1975].

In microbial composting, particle size reduction is mostly achieved by the mechanical turning action, and this depends on the initial particle size distribution. Diaz *et.al.* (1986) conducted a detailed energy balance study on compost production from organic fraction of MSW and sewage sludge, and found that some 15 kWh/Mg of energy was needed to achieve a particle size reduction of raw material to 2.44cm. This characteristic particle size was measured as 63.2% cumulative particles passing through a screen [Diaz *et al.* 1986]. Haug (1993) reported that particle size distribution depends on the type of material added. Sawdust, for example, added as a conditioning agent, should be of 12.5mm in dimension but the same size is not required of a more putrescible waste material due to clogging of inter-particle space. Most of the calculations done in the study were based on mechanical composting on a large commercial scale. Data from small-scale studies or residential units could not be located, so it could not be ascertained whether these cited studies could be used to optimise the vermicomposting process in a small unit.

Given that the process dynamics and moisture content are different in vermicomposting, the above relationship will not be entirely appropriate for application in vermicomposting. Adequate scientific data could not be found in the literature that referred to such relationships in vermicomposting. In microbial composting, the turning action breaks down the already decomposed material thereby reducing the particle size, but in vermicomposting it is only the actions of worms that reduce the particle size. A vermicomposting matrix is not turned, as it would disturb the worms and other insects involved in degrading the waste [Darwin 1945; Huhta and Haimi 1988; Phillips 1988; Jensen 2000]. The action of worms' digestive fluids will dealt with in a chapter on the biology of composting.

4.3 Physical factors affecting the parameters which describe vermicomposting

In composting, process control involves the inter-related factors of heat output, temp, ventilation and water removal [MacGregor *et al.* 1981]. The composting process affects temperature and heat removal, moisture removal rate, particle size reduction and volume reduction of the substrate. Temperature and heat removal are affected by aeration and resulting moisture removal, while particle size and volume reduction are affected by the progress of composting.

4.3.1 Temperature and heat removal

In microbial composting, temperature rises and falls during the entire process [MacGregor *et al.* 1981; Haug 1993]. Temperature is both an effect and cause of heat output. Strom (1985) stated that temperature reflected prior microbial activity (as

effect) and determined the current rate of activity (as cause) [Strom 1985]. Finstein (1980) wrote that the mesophilic microbes that started the degradation in a composting matrix elevated the temperature above the ambient level. As the process continued, temperature rose above the mesophilic range when self-limitation and deceleration of growth occurs. At the higher temperatures, thermophilic microbes started to grow and repeated the cycle. The thermophilic action started to decline at 55^{o}C and became severe at 60^{o} C. This temperature rise reduced the activity and further temperature rise, thus averting a complete self-sterilisation. Temperature stabilised at a peak value sustainable for the microbial population, and then declined further. Researchers who have studied different composting processes have also mentioned this effect [Howard 1935].

Temperature within a composting mass is important for 2 reasons [Stentiford 1986]: i) to maximize decomposition rates; and ii) to produce a material that is microbiologically safe for use. Temperatures above 60-65^{o}C reduced the rate of bio-oxidation in bench scale studies. 55^{o}C was suggested as the optimum temperature for microbial composting action to proceed. Temperatures above 70^{o}C reduce activity and even produce a false indication of process completion. The author mentioned that 55^{o}C for 3 days was enough for pathogen content to be reduced to acceptable levels.

Appelhof (1988) reported that the temperatures of successful vermicomposting operation ranged 4-38^{o}C with a higher rate within 10-23^{o}C. According to various researchers, temperature is not a deciding factor in vermicomposting as far as material conversion is considered, but rather it is a deciding factor for the fate of the

worms and thus the success of the process. Different authors have given different temperature tolerance levels for different species of worms as well as within the same species and for cocoon hatching and somatic growth. Aston (1988) gathered many such data, which showed a total range of 16-29^{0}C for *E. foetida* and 12-18^{o}C for *Lumbricus rubellus* etc. Other authors had given a wider range of temperature tolerance, such as freezing to 35^{o}C for *E. foetida* [Bogdanov 2001].

Cocoon production and hatching always occurs at a lower temperature range than worm growth and life. An increase in ambient or composting matrix temperature could affect this reproduction efficiency. The lifecycle of worms can be divided into 3 phases: cocoon phase, young (immature) phase and adult (mature) phase. Most of the cocoons laid by adult worms are barren (empty or still-cocoons) and the number of these increase as temperature rises [Jefferies and Audsley 1988]. Earlier studies have also confirmed this and indicated that worms try to avoid extreme temperatures, either cold or hot, by migrating away from the area or by burrowing deep down into the matrix or soil [Darwin 1945].

Reports and studies are aplenty regarding the thermodynamics of microbial composting [Schulze 1962; McCarty 1964; Tansey and Brock 1978; de Bertoldi *et al.* 1988; Haug 1993; Miner *et al.* 2001] as well as anaerobic technologies [de Baere and Verdonck 1986; Oorshot 2001; Harikishan and Sung 2003; Onargan *et al.* 2003]. But literature on the effects of temperature in vermicomposting have concentrated on the effects on the worm population, perhaps due to the fact that as higher order creatures, worms react and are affected quickly rather than adapt to changes in

temperature, as a microbial population do [Appelhof 1988; Edwards 1988; Huhta and Haimi 1988; Aranda *et al.* 1999; Bogdanov 2001].

4.3.2 Moisture removal rate (as Hydraulic Retention Time)

The rate of moisture removal is of high importance in microbial composting due to the maximum allowable moisture levels of up to 60% [Haug 1993; Epstein 1997]. But vermicomposting allows or requires a higher moisture level of 80-90% [Phillips 1988; Jensen 1998; Jamieson 2000; Dowdle and Dowdle 2002], so moisture removal becomes a lower priority factor in managing the composting process. Especially in a vermicomposting system designed for wet composting, such as composting of blackwater, the water added should be collected as effluent for further treatment. Therefore, a hydraulic retention time of appropriate duration becomes more important. Conservation of water would not be possible in a microbial composting system that removes the excess moisture through aeration, as discussed in section 4.2.3.

The Hydraulic Retention Time (HRT) of a vermicomposting system depends on the substrate, particularly its porosity and quantity. Bulky items reduce the HRT allowing higher vertical flow rate [Okadora 2000; Jayasekara *et al.* 2001]. Depending on the method of applying the liquid onto the composting mass, there could be a horizontal flow, which would promote the HRT because drier areas of the matrix would act as a sponge and retain water. Smaller interstitial spaces could add to this effect, increasing the HRT and thus improving the pathogen removal. A proper solids retention time (SRT) would also improve pollutant removal and stabilise the solid waste [Zucconi and de Bertoldi 1986; Loehr *et al.* 1988; Finstein 1992; Keener *et al.*

1992; Buckerfield and Webster 2001]. Thus, HRT and SRT become important design parameters, which can be used in deciding the size of the composting chamber (design stage) for the quantity of waste materials treated (operational stage).

A longer HRT would be helpful for waste degradation and pathogen removal because microorganisms show a tendency to stick to the moisture film on solid surfaces [Hoitink and Keener 1993; Todd and Josephson 1996] and the longer HRT and the slower flow would allow higher solids filtration whereby the microorganisms and pathogens in the blackwater could also be filtered to higher levels. Also, proper HRT would allow complex chemical reactions to complete thus further stabilising the solid and liquid wastes [Haug 1993; Droste 1997; Stewart and Ebel 2000].

4.3.3 Particle size and volume reduction – stability indices

Volume reduction and stability dictate the final product quality in composting. Volume reduction in composting occurs through particle size reduction and the resulting compaction. As the process proceeds, the decomposed matter has smaller particle sizes and volume is reduced, the interstitial spaces become small, thus reducing air passage. As the matter becomes stabilised with lower moisture content (approximately 20%), it does not undergo any further decomposition, so the compost matrix does not create anaerobic conditions [Mears *et al.* 1975; Zucconi and de Bertoldi 1986; Norstedt *et al.* 1992].

Haug (1993) has quoted from literature that "complete aeration of all particles would involve reducing all particles to a size less than a millimetre or two, because by its

very dimensions a particle any larger could be anaerobic in its interior". It is argued that final compost particle sizes less than half a millimetre improve diffusion of oxygen due to larger surface area to volume ratio, improving the aerobic nature of the mass.

Studies by Mears *et.al.* (1975) indicated that a higher moisture content of compost, as any other material, lead to higher thermal conductivity, which could lead to continued chemical activity and release of nutrients in volatile form. Compaction also could occur due to the small particle size distribution. Various authors have indicated that good final compost would have the texture of moist loose soil [Nappi *et al.* 1989; Vallini *et al.* 1989]. The mass reduction reported by these and other authors was of 10-40% initial mass for MSW compost [Thompson *et al.* 2001]. Composting of faecal matter has been reported to achieve 75% decomposition [Vinnerås *et al.* 2003].

Stability of mature compost or vermicastings can be assessed by chemical tests, such as the 3-day CO_2 evaluation test or NH_4-N tests for manure composts, or by the newly reported 4-hour Solvita test [Changa *et al.* 2003]. Most of these tests evaluate the generation of CO_2 or ammonia, given off by microbial respiration and other chemical substrate transformation reactions. A coliform test gives indication of pathogen reduction [Nappi *et al.* 1989; Newton 2003]. The final product is reported to provide very high nutrient levels compared to top soil, such as, on average, 7 times the nitrogen, 3 times potassium, twice the phosphorous, twice the calcium etc. [Reddy 1983; Ingham 2000; van Zoest 2002].

The preceding review suggests that the major indices for assessing the stability of a domestic vermicomposting unit that treats blackwater are the reduction of pathogens, suspended solids and dissolved solids in effluent discharge, compost quality in terms of volume and particle size reduction, nutrient levels and lack of odour in the final compost. Specific to vermicomposting as an index of stability is worm biomass yield, which indicates the stability of the process in terms of a self-sustaining worm population that could control its size and number of individuals in each species.

4.4 Conclusion

The different physical aspects of composting are the method of composting (aerobic, microbial, vermicomposting, anaerobic etc), substrate composition in terms of materials treated, aeration, moisture content and removal rate, temperature and heat removal, particle size and volume reduction, HRT and SRT. The process control parameters that should be incorporated into the design stage are HRT, SRT, aeration, method of composting, substrate composition, and moisture content. The parameters that identify constraints for the design of a vermicomposting system to treat domestic solid waste with blackwater are temperature and heat removal, moisture removal, particle size and volume reduction.

Lack of published scientific data on many aspects of interest in vermicomposting is a problem in developing the design of a residential-size system. The major difference in the processing between microbial and vermicomposting systems is due to the difference in the biology of the different organisms involved. The biology of vermicomposting is examined in the next chapter.

CHAPTER 5 THE BIOLOGY OF COMPOSTING

5.1 Introduction

The process of composting is mostly biological in nature, achieved by the actions of different organisms. Composting involves the interactions of different organisms at various levels of the food chain in the different nutrients cycles in the substrate being degraded. The various organisms involved in the process consume the waste materials at different rates, and an understanding of their biology is necessary to design a composting system and its mode of operation. This chapter discusses conventional microbial composting as well as vermicomposting.

5.2 Fundamentals of microbiology

The different chemical and physical reactions and transformations that cause material conversion, volume reduction and pathogen removal in a compost occur by the actions of the microorganisms involved in the process of composting. Whether the process is undertaken as pure microbial composting (mesophilic and thermophilic stages) or vermicomposting, microbes form the basis of life in a composting environment, similar to the natural world. Figure 5.1 shows the classification of the different members of the Protist kingdom, which includes most of the microorganisms of interest involved in the composting process.

Table 5.1 classifies humans, red composting worm and *Escherichia coli* - a microorganism commonly mentioned in wastewater treatment, initially discovered in 1888 by Theodor Escherich [Cullimore 2000; Alcamo 2001].

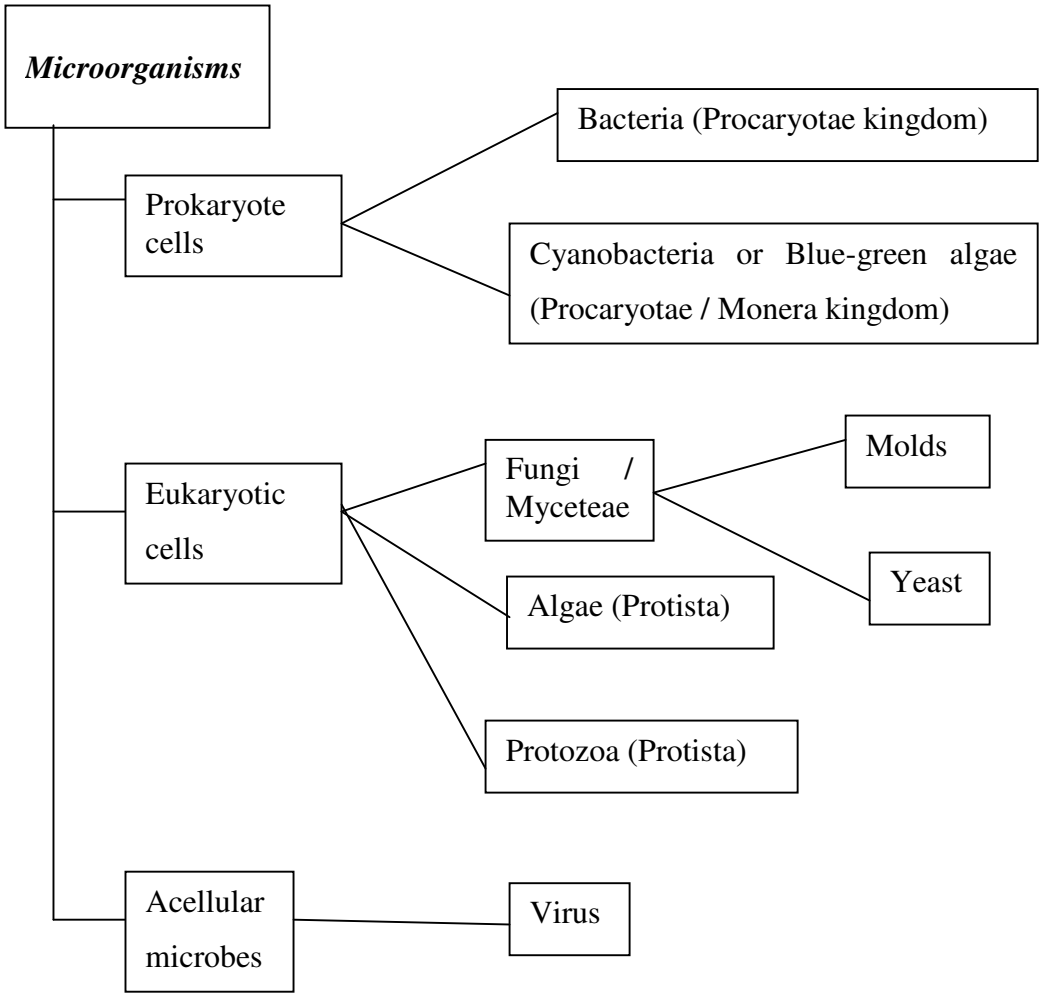

Figure 5.1 Classification of microbes in the Protist Kingdom
(adapted from Haug, 1993).

Bacteria have been known to adapt to the widest living conditions such as the arctic ice, thermal hot springs, hot volcanic ash, outer space and within the bodies of higher animals. Bacteria appear in rod (bacillus), sphere (coccus), spiral and other shapes. There are aerobic (living on oxygen) and anaerobic (live in oxygen free environments) bacteria among several classifications that have been proposed and used in different contexts.

Table 5.1 Examples for biological identification of organism

Common name → / Taxonomical group	Humans	Red worm (composting worm)	Intestinal *E. Coli*
Kingdom	Animalia	Animalia	Prokaryotae
Phylum	Chordata	Annelida	Bacteria
Class	Mammalia	Clitellata (Subclass: Oligochaete)	Schizomycetes
Order	Primata	Lumbriculida	Eubacteriales
Family	Hominidae	Lumbricidae	Enterobacteriaceae
Genus	*Homo*	*Lumbricus*	*Escherichia*
Species	*H. sapiens*	*L. rubellus*	*E. coli*

[AWGAV 2000; ITIS 2002; DSMZ 2003]

Fungi, which often occur in composting systems, have been classified as a separate kingdom in microbiological literature, though they earlier were included in kingdom Plantae [Sullia and Shantharam 1998]. Unlike plants, fungi are filamentous and lack chlorophyll. They reproduce by budding (a new cell grows as a bud on a parent cell), fission and by forming spores. Yeasts are unicellular fungi while molds are multicellular and filamentous (hyphae). Hyphae can branch out forming a network known as mycelia. Yeasts form colonies of spherical or oval shape. Certain fungi can grow in both yeast and mold forms (dimorphism) depending on environmental conditions. For example, *Blastomyces dermatitidis* that grows as a yeast at 37^{o}C and as a mold at 24^{o}C [Wistreich 1999].

Protozoa are unicellular eukaryotes and are an important link in the food chain that completes the decomposition of natural materials. They form one component in the process that converts nutritional elements in materials into substances that higher order animals can utilise, such as conversion of grass within the stomach of grazing animals. They are larger than bacteria, ranging from 10 to 100 µm [Haug 1993] and

are bacterial grazers or bacteriophages [Ingham *et al.* 1985]. Protozoa have been referred to as a subkingdom under the Protist kingdom, with four different phyla: mostly comprising of the amoebae, flagellates, ciliates and the spore forming protozoa [Sullia and Shantharam 1998]. Some protozoa cause diseases such as amoebic dysentery (*Entamoeba histolytica*) and infections (*Giardia lamblia*) [Sullia and Shantharam 1998; Heritage *et al.* 1999; WaterWatch 1999].

5.2.1 Metabolism

Metabolism can be defined as the sum of all biochemical reactions taking place in live cells; and this can be further differentiated into anabolism and catabolism. Anabolism (biosynthesis) is the synthesis of chemical compounds and catabolism is the digestion of chemical compounds [Villee *et al.* 1963]. During anabolism, chemicals are absorbed into the cells where they are converted into useful components. This process demands energy that is available from light and inorganic and organic chemicals digested through catabolism [Sullia and Shantharam 1998].

Microorganisms have been classified based on the metabolic characteristics and the role they play in the element cycles in nature such as carbon cycle, sulphur cycle, nitrogen cycle etc. There are several microorganisms that survive using alternate energy sources to those that most eukaryotes depend on. Eukaryotes have more members of the group, but prokaryotes such as bacteria are more abundant in nature. The latter play key roles in digesting waste materials, and making nitrogen in the air and the waste materials available to plants through nitrogen-fixation and also are the drivers of the carbon, sulphur and nitrogen cycles that form part of the basis of life on earth [Heritage *et al.* 1999; Alcamo 2001].

Carbon Cycle: Many microbes utilise compounds other than oxygen as electron acceptors in their metabolism, unlike all macroscopic organisms and some microorganisms that are obligate aerobes. For example, carbon dioxide has been reported to be used by anoxic microorganisms, which converts it to methane [Haug 1993]. Classification of organisms based on their metabolism includes aspects such as respiratory electron acceptor used or energy source. Autotrophs (lithotrophs) reduce CO_2 to form organic matter or use CO_2 as their sole C-source. Heterotrophs use organic compounds as their source of C and energy. Chemotrophs use inorganic compounds as the source of electrons for the completion of the basic biochemical reactions [Sullia and Shantharam 1998]. Table 5.2 details the different metabolic categories in microbiology.

Photoautotrophs such as cyanobacteria, green plants and algae incorporate CO_2 into organic matter using energy from sunlight. Chemoautotrophs such as *Thiobacillus* and *Beggiatoa* fix CO_2 into organic matter while oxidising compounds such as H_2S for energy. In the next step, chemoheterotrophs such as animals and protozoa consume the autotrophs and the organic compounds in these cells are re-synthesized. Some of the organic molecules are used up by the chemoheterotrophs for energy releasing CO_2 through respiration. Much of the consumed C is either expelled as excreta, or remains in the bodies until the organism dies, after which it is decomposed by bacteria and fungi, releasing further CO_2 [Tortora *et al.* 1998; Cullimore 2000; Alcamo 2001].

Nitrogen Cycle: Bacteria of the genus *Nitrosomonas* are chemoautotrophs that take part in the decomposition of waste materials. They use ammonia as their electron source in a reaction known as nitrification:

$$NH_4^+ + ½\ O_2 + H_2O \Leftrightarrow NO_2^- + 2H_2O + 2H^+ \qquad \ldots 5.1$$

The organic N present in proteins, amines and urea is hydrolysed to ammonia and is then oxidised to nitrate by *nitrosomonas* creating new cells with chemical form $C_5H_7O_2N$ [Arundel 2000] as:

$$55NH_4^+ + 76O_2 + 109HCO_3^- \rightarrow C_5H_7O_2N + 54NO_2^- + 57\ H_2O + 104H_2CO_3 \qquad \ldots 5.2$$

Following this, another genus of chemoautotrophs called *Nitrobacter* utilise nitrite as their energy source in a second stage of nitrification and the reaction could be generally represented as:

$$NO_2^- + ½\ O_2 \rightarrow NO_3^- \qquad \ldots 5.3$$

Detailed reaction for metabolism and cellular synthesis reaction as given by Arundel (2000):

$$400NO_2^- + 195\ O_2 + NH_4^+ + HCO_3^- + 4\ H_2CO_3 \rightarrow 400NO_3^- + 3\ H_2O + C_5H_7O_2N \qquad \ldots 5.4$$

Table 5.2 Classification based on Metabolism

Respiration	**Metabolism**	**Energy source**	**C-source**	**Reductant**	**Oxidant**	**Product**		**Representative organism**
Aerobic	Photoautotroph	Light	CO_2	Organics		O_2, H_2O		Higher plants, algae, bacteria
Aerobic	Photoheterotroph	Light	Organics					Algae, bacteria
Aerobic	Lithoautotroph	Inorganic reduction-oxidation reactions (I)	CO_2	NH_4^+, NH_3	O_2	NO_2^-, H_2O		*Nitrosomonas*
Aerobic	Lithoautotroph			NO_2^-		NO_3^-		*Nitrobacter*
Aerobic	Lithoautotroph			S^{2-}, H_2S		SO_4^{2-}		*Thiobacillus*
Aerobic	Lithoautotroph			Fe^{2+}		Fe^{3+}, H_2O		*Ferrobacillus*
Aerobic	Lithoautotroph			H_2		H_2O		*Hydrogenomonas*
Aerobic	Organoheterotroph	(O)	Organics			H_2O, CO_2		Higher animals, many bacteria
Anoxic	Lithoautotroph	(I)	CO_2	Fe^{2+}	NO_3^-	Fe^{3+}, N_2, H_2O		*Ferrobacillus*
Anoxic	Organoheterotroph	Organic red-ox reactions (O)	Organics			H_2O, N_2, CO_2		*Pseudomonas, Clostridium*
Anoxic	Organoheterotroph				SO_4^{2-}	H_2O, H_2S, CO_2		*Desulfovibrio*
Anaerobic	Organoheterotroph		Organics			CH_4, CO_2		Acidogens, methanogens
Anaerobic	Lithoautotroph	(I)	CO_2	H_2	CO_2	CH_4, H_2O		*Methanobacteria, Methanococcus*

[Villee *et al.* 1963; Finstein and Morris 1975; Haug 1993; Sullia and Shantharam 1998; Tortora *et al.* 1998; Wistreich 1999; Cullimore 2000; Alcamo 2001]

Certain anaerobes such as *Clostridium* utilise nitrate as their electron acceptor while metabolising other energy sources in a process called denitrification, reversing the above reactions and finally releasing gaseous N. Metabolic oxidation of 1 mg of ammonia N to nitrate-N requires 4.3 mg of oxygen [Sullia and Shantharam 1998; Tortora *et al.* 1998; Sánchez-Monedero *et al.* 2001]. As evident from the above reactions, alkalinity of the waste material reduces and the pH lowers into acidic range during the nitrification reactions.

The biochemical reactions of metabolism are catalysed by enzymes made up of proteins. Some enzymes have been extracted for their beneficial properties, such as *catalase*, which is reportedly powerful enough to decompose 5 million molecules of H_2O_2 per minute at 0^oC [Villee *et al.* 1963]. Some enzymes are very specific to one task, such as urease that decomposes urea into ammonia and CO_2, and does not affect any other substance. Some others such as peroxidase work on a range of related substances such as peroxides and some are used as histological markers [Wilkipedia 2004].

The enzyme called adenosine triphosphatase (ATPase) is a very important enzyme for all living organisms for the energy transfer among cells. All cellular reactions require the chemical energy released when ATPase catalyses the breaking of a high-energy bond within the unstable molecules of a compound called ATP (adenosine triphosphate) producing ADP (adenosine diphosphate) and a phosphate group. ATP is a high energy molecule whereas ADP is at a lower energy state [Crites and Tchobanoglous 1998]. It has been estimated that a single mole of ATP, weighing 507

grams, releases 30.56 kJ of energy; and that an adult human uses up approximately half the body weight of ATP per day [Alcamo 2001].

The ADP molecule recaptures the energy released in the breakdown of organic/inorganic molecules that serve as energy source, recombines with the free phosphate group and becomes ATP. Chemoautotrophs and chemoheterotrophs utilise the energy from oxidation of inorganic and organic compounds, respectively, for the synthesis of ATP. Photoautotrophs and photoheterotrophs convert light energy through oxidative phosphorylation of chlorophyll and other pigments into chemical energy, which is then utilised for the synthesis of ATP [Crites and Tchobanoglous 1998; Tortora *et al.* 1998].

5.3 Microorganisms in waste treatment

In the 1880s, Martinus Beijerinck and Sergei Winogradsky reported extensively on how bacteria help recycle vital elements between soil and the atmosphere - paving way for the development of Microbial Ecology [Nilsson *et al.* 2000; Alcamo 2001]. Bacteria, such as *Pseudomonas* and *Bacillus* spp., are used in bioremediation due to their ability to use pollutants as their energy source or produce enzymes that convert the chemicals into harmless by-products [Tortora *et al.* 1998].

The various organisms that are beneficial in waste treatment use the energy released from the catabolism of different organic molecules such as proteins, lipids and fats, glucose, other carbohydrates etc in synthesizing ATP. Proteins are broken down into amino acids, which then undergo deamination reactions. Fats are converted into simpler organic molecules through beta-oxidation processes [Alcamo 2001].

The energy released depends on the complexity of the molecule, the types and strength of different chemical bonds that make up the molecule as well as the process of catabolism. For example, the synthesis of protein by prokaryotes and eukaryotes involve different processes of 'transcription' and 'translation', which incorporate different reactions [Sullia and Shantharam 1998]. Approximately 100,000 species of fungi have been found to excrete powerful enzymes that play a major role in biodegradation of waste [Todd and Josephson 1996]. Protozoans have been found to be saprophytic (primary feeders of raw waste organics) and predators of prokaryotic and other eukaryotic organisms. The presence of certain protozoa has been identified as indication of high DO and lower dissolved organic pollutants [Droste 1997].

The effectiveness of biological treatment of wastes can be assessed by the effects of the oxidation reactions such as reduction in BOD and oxidation of ammonia to nitrate [Arundel 2000]. Reduction of organic matter causes endogenous respiration or the utilisation of cell material for respiration by microorganisms without replacement, leading to a drop in cellular mass [Crites and Tchobanoglous 1998]. Reduction in lower microorganisms in turn would lead to reduction in predatory microorganisms.

Different methods of microbial waste treatment are available, such as aerobic composting, anaerobic digestion, fermentation, contact biofilm processes etc. In aerobic composting biodegradable waste materials are treated with aerobic heterotrophs and autotrophs while in anaerobic digestion favourable conditions for anaerobic microorganisms are provided. The beneficial properties of microbial metabolism of different organic molecules have been put to use for treating oil-

spillage as well as for oil-extraction from sludge [Al-Daher *et al.* 2001; Oorshot 2001; Vitello 2001].

Microbial composting has been described as 'microbiological engineering' or 'engineering with microbes' [Haug 1993]. Hogan *et.al.* (1991) identified composting as a process based on the phenomenon of microbial self-heating of organic assemblages in which a moist solid-phase (organic particles) interfaces with a gas phase (interstitial air). This material/matrix is its own source of organic and inorganic substrates, water, and inoculum and has its own thermal cycles that start with self-heating, temperature elevation, mesophilic and thermophilic stages etc. The first stage, mesophilic stage, has a peak heat generation at 35^0 C, then as the temperature rises, a mesophilic self-destruction happens at 45-50^0 C and the thermophilic stages begins, which again undergoes a 'microbial suicide' at temperatures above 65^oC, returning to mesophilic ranges [Hogan and Finstein 1991]. As a result, material conversion occurs including particle size reduction. It has been reported that compaction in the matrix can cause anoxic conditions that can replace the aerobic composting process with fermentation [Rich and Andrews 1964; Tansey and Brock 1978; de Baere and Verdonck 1986; Hammes *et al.* 2000; Enejii *et al.* 2003].

Composting progresses through different stages and elemental cycles as described in chapter 3. The two most important elemental cycles, the carbon cycle and nitrogen cycle, describe most of the important biochemical reactions taking place in a decomposing waste matrix.

Nilsson *et.al.* (2000) reported that the natural products of microbial metabolism of the organic components in biowastes were hydrocarbons (H-C), fatty acids, fatty acid esters, *n*-alkanes, aliphatic alcohols, monoterpenes and triterpenes as well as some other complex chemical groups. They reported that chromatographic tests on the extracted gaseous products of mesophilic and thermophilic stages of microbial composting showed differences while a comparison of the two phases in anaerobic reaction did not give such variation [Nilsson *et al.* 2000].

Anaerobic pockets always existed in aerobically decomposing matrices and lack of oxygen could lead to the spread of anaerobic microbial reactions that produce a wide variety of volatile fatty acids (VFAs) and other gaseous products [Shin *et al.* 2001; Wiles *et al.* 2001]. This leads to the possibility of the generation of foul odours, which is the main disadvantage of anaerobic processes compared to aerobic processing.

Methane gas is a product from anaerobic metabolism. Anaerobic reactions within landfills give off large quantities of methane during the initial years [Streese and Stegmann 2003]. In all microorganic waste conversion processes, all types of bacteria could be initially taking part including pathogenic organisms. The numbers of particular organisms reduce as a result of the environmental conditions such as nutrient availability, temperature and presence of other organisms.

5.3.1 Pathogen removal – effect of different aspects

A most important aspect of biological waste treatment is the reduction of harmful pathogens, including certain bacteria, viruses, protozoa and others. In microbial

composting, pathogen destruction is a result of competition with composting microbes for the available nutrients, high temperatures encountered in the thermophilic stages and some of the intermediate metabolites secreted by microbial respiration [Farrell 1993; WaterWatch 1999; Sidhu *et al.* 2001]. Control of pathogens in waste treatment facilities has been subject of legislation in most parts of the world and specific guidelines and standards have been proposed and enforced by relevant authorities.

The release of energy upon metabolitic activities by the microorganisms causes a temperature build-up that in turn increases the rate of material conversion and thermal inactivation of pathogens. The temperature profile of microbial composting has been well documented in literature. Microbial composting heaps keep the heat released by respiration of microorganisms decomposing the organics, thereby increasing the temperature within a composting heap by the natural insulation of the matrix. This is a major difference between composting and natural degradation of organic matter in nature [de Bertoldi *et al.* 1983].

Excessively high temperatures inhibit bacterial growth (microbial suicide) with only a very few species of thermophiles showing metabolic activity at temperatures above 70^{o} C (*Bacillus stearothermophilus, Bacillus subtilis, Clostridium* sp. and non-sporigenous gram negative aerobes of the genus *Thermus*). Therefore high temperatures for long periods should be avoided for rapid composting. The thermosensitive pathogens will be removed by an initial phase in the thermophilic stage. Optimum temperatures vary between 45-55^{o}C [de Bertoldi *et al.* 1983]. Other authors mentioned that 55^{o}C for 3 days is enough for pathogen reduction to

acceptable levels, reducing pathogens considerably even in the cooler regions in the composting mass [Stentiford 1986]. Most species of microorganisms cannot survive at temperatures above 60-65°C [Trautmann and Richard 1995]. In anaerobic digestion of wastewater, mesophilic reactions have been reported to achieve 1-2 log reductions in pathogens while thermophilic stages achieved 3-4 log reductions in the numbers [Baeten and Verstraete 1992; Droste 1997; Hammes *et al.* 2000].

The pathogenic organisms of interest in composting are total enteric viruses, total parasites, parasitic helminth *Ascaris* ova, *Yersinia* sp.*, Campylobacter* sp.*, Salmonella*, total enteric bacteria, enterotoxigenic *E.coli,* bacteriophages, total and thermophilic fungi, aerobic and anaerobic plates, faecal streptococci and faecal coliforms [Farrell 1993]. Table 5.3 provides information regarding some pathogens encountered in waste materials and the diseases they could cause.

Many of these pathogenic microorganisms are not able to infect their final host directly, but only through specific pathways of food chain or other contacts. Most have evolutionary constraints that cause them to perish in the harsh environment outside the host's body [Heritage *et al.* 1999]. This is an added advantage of biological waste processing techniques as many non-pathogenic microorganisms are also concentrated in the compost and compete for the available nutrients. Farrell (1993) confirmed that viruses and helminths would not be able to regrow once their numbers have been reduced to safe levels.

Table 5.3 Pathogens and diseases

Type of organism	Microorganism	Disease/symptom
Bacteria	*Vibrio cholerae*	Cholera
	Salmonella typhi	Typhoid and other enteric fevers.
	Salmonella other species	Food poisoning.
	Shigella species	Bacterial dysentery.
	Campylobacter	Gastro-enteritis.
	Proteus species	Diarrhoea
	Coliform species	Diarrhhoea
	E coli 0157	Gastro-enteritis, renal failure
	Clostridium species	Botulism
	Pseudomonas species	Local infection
	Tubercle bacilli	Tuberculosis
	Leptospira	Leptospirosis (Weil's disease)
	Yersinia enterocolitica	Gastro-enteritis
	Yersinia pestis	Black Death
Virus	Hepatitis A – RNA virus	Infectious Hepatitis – Inflammation of liver
	Hepatitis B – DNA virus	Hepatitis B
	ECHO virus	Enteric disease and the causative agents of asceptic Meningitis
	Coxsackie virus	
	Polio virus	Poliomyelitis
	Gastroenteritis virus	Gastro-enteritis
	SRV (small round viruses)	Gastro-enteritis
	Herpesviridae	Herpes
	Rhabdoviridae	Rabies – acute encephalitis
	Rotavirus	Diarrhoea
	Orthomyxoviridae	Influenza
	Retroviridae	Cancer, HIV
	Papovaviridae	Cancer
	Poxviridae	Small pox
Protozoa	*Entamoeba histolytica*	Amoebic dysentery
	Balantidium coli	Balantidial dysentery
	Isospora hominis	Coccidiosis
	Giardia Lamblia	Diarrhoea
	Crytosporidium sp.	Epidemic diarrhoea
Helminths	Cestodes (tapeworms)	Infections in pet animals
	Nematodes (roundworms)	Ascariasis, onchocerciasis, tricuris, filariasis, elephantiasis.
	Trematodes (flukes)	Fasciolpsiasis, paragonimiasis, infections in animals.

[Heritage *et al.* 1999; WaterWatch 1999; Wistreich 1999; Alcamo 2001]

Inspection for all microorganisms has always been impractical due to cost and difficulty involved, and this has lead to the identification of certain specific indicator organism groups such as faecal coliforms. These are chosen based on their survival

rate in all water sources, their presence with pathogens and inability to reproduce in the water sample [Clesceri 1999; Newton 2003]. The three faecal indicator organisms are *E. coli, C. perfringens* and enterococci [Heritage *et al.* 1999], with *E. coli* being preferred. In most cases, the number of indicator organisms almost equal the number of faecal coliform [Newton 2003]. Reduction in indicator organisms has been accepted as safe indication of pathogen removal. Droste (1997) used an empirical model based on the Arrhenius equation to calculate indicator microorganism die-off in aerobic digestion:

$$k = \frac{\log_{10} C_0 - \log_{10} C_e}{\theta_d}$$

where k is the empirical rate coefficient, C_0 and C_e are the influent and effluent indicator densities in CFU/100ml and θ_d is detention time in days.

5.3.1.1 Pathogen removal by disinfection

Where the natural pathogen removal has not been to satisfactory standards as prescribed by relevant guidelines, forced pathogen killing is employed by different techniques of disinfection. This has been the practice with waste and wastewater treatment as well as potable water treatment around the world. The techniques employed are physical or chemical in nature, depending on the level of treatment required. The physical agents destroy all life forms including bacterial spores and achieve 'sterilization', while most chemical agents remove only pathogens and achieve 'disinfection'.

The agents employed in centralised water treatment plants are alum as a coagulant that gives 1.5 log reduction and chlorine that gives up to 6.5 log reduction of

coliform counts [Arundel 2000]. Chlorination is the most widely used final disinfection technique in water purification. Chlorine is usually applied in water as chlorine gas (liquid chlorine is sometimes used as a source in centralised water purification) or as chlorine dioxide (ClO_2) or as calcium hypochlorite ($Ca(OCl)_2$ – chlorinated lime) or as sodium hypochlorite (NaOCl) [Eckenfelder 1991; Sincero and Sincero 1996]. Chlorine rapidly hydrolyses in water as per the reaction:

$$Cl_2 + H_2O \Leftrightarrow HOCl + H^+ + Cl^- \quad \ldots 5.5$$

Usage of hypochlorite is also based on the disinfecting power of HOCl:

$$Ca(OCl)_2 + H_2O \Leftrightarrow Ca^{2+} + H_2O + 2OCl^- \quad \ldots 5.6$$

$$OCl^- + H^+ \Leftrightarrow HOCl \quad \ldots 5.7$$

This hypochlorous acid is unstable and it undergoes the reverse reaction under favourable conditions of temperature (warm) and pH (acidic) [Eckenfelder 1991].

Chlorine removes the microorganisms by affecting the metabolism or reproductive capabilities of the cell. It frees up and combines with the oxygen atoms in the cells thus inactivating certain cyto-plasmic proteins such as enzymes. It could also cause breakage of the cell membrane, leading to leakage of the cellular protoplasm [Alcamo 2001].

Application of chlorine is done only as a final step in water treatment, as presence of organic matter could inactivate the element through various reactions. Chlorine reacts with fulvic and humic acids producing undesirable trihalomethanes (THM) such as chloroform and bromochloromethane which are carcinogens [Sincero and Sincero 1996].

Ozone is a very strong chemical disinfectant used in purification of water. The ozone molecule dissociates into oxygen molecule and nascent oxygen that reacts with molecular oxygen in the microorganism cell to form ozone, thus affecting the metabolism [Droste 1997; Alcamo 2001]. When a few ozone molecules come into contact with a bacterial cell, the molecules penetrate the cell wall thus creating a hole (each) that cause cell lysing and breakage [Ozone-solutions 2003]. Crites and Tchobanoglous (1998) have confirmed this and gave the following chemical reaction formulae for ozone in wastewater:

$$O_3 + H_2O \rightarrow HO_3^+ + OH^- \rightarrow 2HO_2 \quad \ldots 5.8$$

$$O_3 + HO_2 \rightarrow HO + 2O_2 \quad \ldots 5.9$$

$$HO + HO_2 \rightarrow H_2O + O_2 \quad \ldots 5.10$$

[Crites and Tchobanoglous 1998]

Lack of any residues and by-products has been the reason for acceptance for ozonation as a strong disinfection mechanism. It has been indicated that a few highly unstable carcinogenic compounds are produced, which disappear in a matter of only minutes [Ozone-solutions 2003].

A physical disinfection technique used in water purification is ultra-violet (UV) radiation at 254nm wavelength. A combination of ozonation and UV radiation has also been in use [Eckenfelder 1991]. This radiation penetrates the cell-wall membrane (if it exists) of microorganisms and get absorbed by cellular materials such as DNA and RNA, causing their alteration [Crites and Tchobanoglous 1998].

Being a physical process, this type of disinfection would not usually produce any by-products.

Conway (1998) has reported another disinfection technique that utilised ionisation technology. A precise, low-voltage DC current at milliamp levels is passed through two silver and copper electrodes, causing some of the outermost atoms of the electrodes to lose an electron, making them positive ions. These copper and silver ions disperse into the moving water. Electrostatic bonds created between the positive ions and negatively charged microbial cell membrane result in stresses that distort cell-wall permeability and minimize the normal intake of life-sustaining nutrients. Once inside the cell, copper and silver attract sulphur-containing amino acid residues in the proteins. As a result, the basic processes of metabolism and cell synthesis is blocked leading to cell lysis and microbial death.

Copper has long been known as an effective algaecide, and silver has been very effective at killing bacteria and viruses. Silver sulphate is the standard antibacterial treatment for burns and open wounds, and for many years was used to protect the eyes of newborns. Activated carbon filters are impregnated with silver to prevent bacterial build-up [Conway 1998].

5.4 The Biology of Earthworms

Earthworms have been known to humans for many centuries as soil-dwelling creatures that inhabited almost all parts of the planet. The earthworm has been mentioned in history dating as far back as the times of Aristotle who had dubbed the earthworm as "the intestines of the earth", and Cleopatra who had protective laws

[AWGAV 2000]. Charles Darwin demonstrated that earthworms improve soil conditions and enhance plant productivity. Darwin (1945) studied worms extensively and contributed immensely towards the interest shown towards them in later years. He found out that different species of worms inhabit different geographical locations and different altitudes. Many of his findings have been confirmed by later authors [Hayes 1983].

The body of a large worm consists of 100 to 200 almost cylindrical rings or segments, each covered with the minute bristles. With a well-developed muscular system, they crawl forwards as well as backwards. Worms are hermaphrodites, in that each worm has both sexes. Two individuals pair together, both bearing eggs later. The mouth is at the anterior end of the body, and at the posterior end is situated the vent for excreting [Darwin 1945; LCC 2002].

Worms that are sexually mature have a prominent 'band' around their body, called the 'clitellum'. During mating, the worms will join together at the clitellum (sometimes for quite a long period of time) and reproductive material is exchanged. When the worms separate, a ring of mucus material forms at the clitellum of each worm. The worms then wriggle backwards, and the mucus ring slips off over the head. The ring seals, forming a 'capsule' (also called an 'egg') sealing all the necessary reproductive materials inside. The capsules are opaque white at first (and soft), quickly hardening and changing to a yellow colour. Over the next 3 weeks (depending on environmental conditions), the colour changes from yellow to a rusty brown colour. The capsule will then hatch, producing 2 - 20 baby worms (average 4). It is also possible for some worms to reproduce by themself, particularly if the

species survival is threatened [Bouché 1983; Satchell 1983; AWGAV 2000; Irishearthwormcompany 2002].

Worms lack senses of vision, hearing and smell, as they do not have eyes, ears and nose. They breathe, sense light, heat and vibrations through the skin. Their ability to sense light enables them to distinguish between day and night. It has also been shown that some worms get out of their earthly burrows and crawl about the grass after a large tremble is felt. Their entire body is sensitive to contact [Sosnowski 1982; Jamieson 2000; Jensen 2000; Slocum 2000a, 2000b].

Studies have shown that worms are able to sense UV radiation. A certain time-lapse is observed between the occurrence of intense light and the retrieval action by worms. Worms appeared less sensitive to moderate radiant heat than to a bright light [Jefferies and Audsley 1988; Fraser-Quick 2002]. Some tests with cabbages and onion showed that they possess some degree of sense of smell [Leischner 2000].

Their sense of taste has been proven by their likes and dislikes that they display towards some food items. Generally earthworms are omnivorous, they devour most organic matter, but some items are preferred to others. A few species were found to prefer raw fat to raw meat or anything else [Ingham 2000; Fraser-Quick 2002; Hendrix and Bohlen 2002]. Some were found to decompose the bodies of dead worms. The worms consume the substrate after moistening with a secreted fluid, alkaline for most worms. This fluid is found to discolour fresh leaves though it might be particular for individual species of worms. Their castings are mostly acidic. It is also reported that the humus acids generated during the worm-action is strong

enough to disintegrate rocks. Haddon (1993) had found that the worm castings tend to have acidic to neutral pH.

Earthworms, including composting worms, are included in the kingdom Animalia, phylum Annelida, class Clitelatta and subclass Oligochaetae. Worms of different lower taxonomical groups have been known to show comparable or similar properties [AWGAV 2000; ITIS 2002; DSMZ 2003]. Most worms are known with three names, the name of their discoverer added to their binomial nomenclature, such as *Lumbricus terrestris* Linnaeus (night crawler worm) [Sims 1983].

Over 4400 species of earthworms have been recognised and classified as epigeic (litter dwelling), anecic (burrowing, soil dwelling) and endogeic (deep soil) [Bogdanov 2001]. The third group can be further classified as oligo-endogeic, meso-endogeic and polyhumic endogeic . Epigeic worms have been shown to be able to survive on waste material alone, and they are not dependant on soil unlike the two other types of earthworms [Haddon 1993]. There are significant differences among worms, the epigeic type being much smaller in length compared to anecic and endogeic - The length of adult earthworms range from 10mm in the smaller worms to more than a metre, with corresponding increase in width/thickness in giant endogeic earthworms such as *Megascolides australis* and *Digaster longmani* seen mostly near the east coast of Australia [Jamieson 2000, 2001]. Generally, the anecic nightcrawler worms are larger than the purely epigeic worms, both of which are used in composting.

A few studies have been reported that focus on or mention the general life of earthworms used in composting [Bouché 1983; Lavelle 1983a, 1983b; Kauffman 1993; Kaviraj and Sharma 2003]. Lavelle (1983b) estimates up to a million worms per hectare earth with 2 tonnes of worm-biomass.

The lifecycle of a worm could be divided into 3 phases: cocoon phase, young (immature) phase and adult (mature) phase. Many of the cocoons that are laid by adult worms are barren (empty or still-cocoons) with their numbers increasing at higher temperatures. A population model used by Jefferies and Audsley (1988) divided the phases into further stages and defined probabilities of a worm moving from one stage to another stage in a basic time interval [Jefferies and Audsley 1988].

5.5 Worms in Waste Management

When worms are used for composting, the process is termed vermicomposting. The concept of vermicomposting started with the knowledge that certain species of earthworms (epigeic) grow and consume organic waste rapidly compared to other anecic and endogeic earthworms [Aranda *et al.* 1999]. Compared to microbial composting, vermicomposting is faster as worms and microbes are used to digest waste material [Edwards 1988; DNR 2001]. Charles Darwin was the first to write that worms could be used in converting organic waste into a fertiliser. In this regard he could be named the father of vermicomposting.

Vermiculture is activity of growing worms for trade and vermicomposting is the process of worms decomposing waste [TNRCC 2001]. Worm castings (worm excreta) which are encased in mucus membranes secreted by the earthworms contain

plant nutrients, the casing dissolves slowly rather than allowing immediate nutrient leaching. Vermicompost includes worm castings, some earthworm cocoons, inert materials such as sand and rocks, fibrous and woody material and some undigested waste material that continues to be decomposed by the indigenous bacteria [Bogdanov 2001]. The castings are a saturated paste, high in plant nutrients and digested organic matter [Satchell 1983].

Aranda *et.al.* (1999) offered a definition of vermicomposting: "The combination of biological processes, designs and techniques used systematically and intensively to culture large quantities of certain species of (litter dwelling - epigeic) earthworms to speed up the stabilisation of organic waste materials which are eaten, ground and digested by the earthworms with the help of aerobic and some anaerobic microflora, and thereby naturally converted into much finer, humified, microbially active castings where important plant nutrients are held in a form much more soluble and available to plants than those in the parent compound".

Worms have been referred to as eating machines, the waste material and all the microbes passing through their tunnel-like body. The digestive process converts the substrate into worm excreta, termed vermicastings, which is usually a stable material full of plant nutrients and soil microbes. These microbes come from the indigenous microbial community in the waste matrix, only the strong ones being able to escape the gut enzymes of worms. Pathogens within the waste mass usually don’t survive this process. Most pathogenic organisms prefer anaerobic conditions found in the guts of humans and other creatures and are less prepared to survive in the world outside [Aston 1988; Eastman 1999; Vermitechsystems 2001].

Some species are native to temperate climate, such as *Eisenia foetida, Dendrobaena veneta & Lumbicus rubellus*, while some come from the tropics such as *Eudrilus eugeniae & Perionyx excavatus.* So accordingly, it could be expected the favourite diet of worms will show locally adapted variations.

Table 5.4 Comparison of different worm species

Worm sp.	Maturity (days)	Ave. rate of reproduction (worm/wk)	Egg maturing (days)	Cocoon hatching (days)	Mean mature weight (g)	Biomass production (g/week)
Eisenia foetida	53-76	10.4	85-149	32-73	0.55	0.68
Eudrilus eugeniae	32-95	6.7	43-12	13-27	4.3	5.76
Perionyx excavatus	28-56	29.4	44-71	16-21	1.3	6.3
Dendrobaena veneta	57-86	1.4	97-214	40-126	0.92	0.16

[Edwards 1988; van Zoest 2002]

There is a wide variation in the growth pattern in different species of earthworms that are capable of decomposing biowaste (Table 5.4). Worms are chosen based on their reproductive rate and ease of handling [Dowdle and Dowdle 2002]. The most widely used worm *E. foetida* is reportedly tough, can withstand wide temperature conditions and become dominant in any group [Tynes 2000a; ROU 2002b], at different moisture conditions and ammonia levels. At all temperature levels, this worm shows optimum growth (weight) at moisture close to 85%. The number of live worms reduces drastically at ammonia levels more than 1 mg NH_3/g waste and is almost nil close to 3.5 mg NH_3/g waste [Edwards 1988]. Hence, fresh poultry manure kills worms very fast, as does large amounts of inorganic salts.

In this study pig waste was used as a substitute for human waste. Pig waste contains some ammonia and some inorganic salt, so direct vermicomposting is not appropriate. Normally it is composted for 2 weeks prior to inoculation into a vermicomposting unit [NSW 1996]. Aged solid pig waste has been reported to be among the best materials to grow worms, and cattle waste is the easiest and most favourable material for worms. Generally, all organic wastes are excellent for worms except chicken manure [Edwards 1988].

Appelhof (1988) mentioned the apparent lack of knowledge, among public, of the concept of vermicomposting to manage household kitchen waste and their willingness to take up the technique once they learned about it. The reported temperatures of successful operation ranges between 4^{o}C and 38^{o}C with a higher rate within 10-23^{o}C. This means a layperson can undertake vermicomposting to manage common household waste [Appelhof 1988]. A scarcity of supportive scientific data for vermicomposting, with a plethora of ad hoc reports based on individual experiences is present in the literature.

Heat tolerance of worms, as with other poikilotherms (cold-blooded creatures), will be affected by the temperatures they are naturally acclimatised to, duration of exposure and relative humidity of the surroundings [Villee *et al.* 1963]. In light of this, aeration plays a vital part in success of vermiculture, as air circulation controls the temperature within a composting mass. Worms are extremely sensitive to ultraviolet radiation, which causes a temperature rise in their body, so vermicomposting units have to be protected from light. If exposed to sunlight, worms either migrate to dark areas or perish [Dowdle and Dowdle 2002].

Aston (1988) studied the use of many worm species in vermicomposting and the effects of different factors on them. High mortality was observed in many worms at maximum temperatures as low as 25.6^{o}C for 48 hours exposure. Other literature have reported more than 30^{o}C for *E. foetida* (the most commonly used worm) [Aston 1988]. Recent studies have shown their adaptability to a wide variety of substrate materials [Huhta and Haimi 1988; Vigueros and Camperos 2002; Kaviraj and Sharma 2003; Maboeta and van Rensburg 2003]. A comparative study using different mixes of cattle manure with fly ash, vermicomposted with *E. foetida*, showed that an equal mix yielded the highest P-availability [Bhattacharya and Chattopadhyay 2002]. This illustrates the fact that such industrial waste could be subjected to vermicomposting successfully.

Generally, tiger worms (*Eisenia foetida*) are preferred in vermicomposting [Vermitechsystems 2001; Dowdle and Dowdle 2002; van Zoest 2002; ROU 2002b] because:

- They can stand temperatures from freezing up to more than 30^{o} C
- They are fast breeders, eggs hatch in a couple of days
- Good production of cocoons and good hatching rates
- Mature earlier, in one week
- Double their biomass in 2-3 months
- Eat 50%-100% their body weight of waste / day
- Can contain more than 2000 adults / kg live worm- mass

A paper by Buchanan *et.al.* (1988) compared different compost samples made by *E. foetida* from different substrates as well as different composting techniques with regard to nitrogen cycle. The different substrates used were: municipal sewage sludge, tannery sludge with equal manure, vegetable and yard wastes, fresh and aged manure as well as a blend of horse and rabbit manure (35%) mixed with pulverised fir bark (65%). Chemical testing was done for pH, organic-N, ammonium-N, nitrate, T-P, T-K, Ca and Mg on fresh cleaned soil sample, and then the soil after amending with different composts for mineralisation of N [Buchanan *et al.* 1988]. The C-content of earthworm composts seemed consistent with their physical appearance and the N-mineralisation was better during the first week of compost incubation than later.

Many studies have been undertaken on the subject of chemicals and their effects on earthworm populations and this has led to their use as a key bioindicator for some pollutants in soil [Bouché 1988; Callahan 1988; Goats and Edwards 1988]. Most lab tests reported consistent and reproducible results from standard number of worms in intimate contact with the polluting chemicals, under controlled conditions. In a real world situation, there are more factors involved in determining an earthworm's use as a bioindicator. For example, Goats and Edwards (1988) reported that *E. foetida* survived poorly in natural soils under test, though this species is known be tough.

A population model was generated specifically for *E. foetida* regarding organic waste conversion [Mitchell 1983], which could find applications in large-scale industrial uses of vermiculture.

Hotler (1983) studied the capability of earthworms in decomposing cattle droppings in nature. He reported that the material attracted earthworm populations and as the quantity of fresh manure reduced, so did the earthworm numbers. The material had attracted a few insects and insect larvae along with dung beetles, and the numbers of worms had been noted to increase in the presence of such insects [Hotler 1983].

Earthworms have been cultivated for biomass production for aquaculture and poultry farms due to a high proportion of protein (up to 71% dry weight). Disease-fighting drugs have been derived from earthworms [Sabine 1983]. The most preferred composting worm, *E. foetida*, has been found to be suitable in aquaculture as well, due to its high proliferation rate [Hartenstein 1983]. Composting worms have also found application in fruit farms [Mba 1983] as well as dairy farms as a waste management tool [Hatanaka *et al.* 1983]. The most common composting worms are listed in table 5.5. Figs 5.2 & 5.3 show two of these worm species.

Figure 5.2 European nightcrawler worms

Figure 5.3 Red worm

Earthworms behave very differently in an actual system compared to a lab culture [van Zoest 2002; ROU 2002b]. This means that we still can not predict what the simple earthworms do in waste composting, what they prefer as their food, whether waste materials or the microorganisms in the waste, and how they are able to convert so much of waste in a day. There are still issues about how their digestion processes discriminate among indigenous and pathogenic microbes (apparently filtering the population and destroying the latter). It is possible that pathogenic microbes do not have a strong enough structure to withstand the enzymes within the gut of worms as these microbes are adapted to the human gut that lacks these particular enzymes. Indigenous waste-decomposing bacteria appear to have adaptability powers. It has been generally observed that hybrid or so-called 'superworms' do not have any advantages over naturally occurring communities of red wiggler or night-crawler worms [Bogdanov 2001].

Table 5.5 Commonly used composting worms

Common name	**Zoological name**
Red worm	*Lumbricus rubellus / Lumbricus terrestris*
Red tiger	*Eisenia andrei*
Tiger worm / red wiggler	*Eisenia foetida*
Indian blue worm	*Perionyx excavatus*
European nightcrawler	*Dendrobaena veneta / Eisenia hortensis*
African nightcrawler	*Eudrilus eugeniae*

[LAC 2001; LCC 2002; Werner 2002; Slocum 2003]

5.5.1 Insects of interest in organic waste treatment

One major difference between microbial composting and vermicomposting is the presence of insects. Higher temperatures in microbial composting keep insects away [IFAS 2002]. In vermicomposting, other than the introduced composting worms, a

good number of other organisms such as white worms – also called pot worms (entrachyadids) - and many species of insects also take part in the decomposition of organic wastes. The presence of the white worms might indicate acidic conditions that would need pH adjustment. Pot worms and several insects such as dung beetles, mites, spiders, slater bugs, centipedes, millipedes and ants naturally join the process and don't need to be introduced into the matrix [Dominguez *et al.* 1997; Riggle 1998; Ingham 2000; Dowdle and Dowdle 2002; van Zoest 2002; ROU 2002b]. Unfortunately, not much literature could be located that dealt in sufficient depth with the role of these insects in vermicomposting.

The occurrence of insects is dependant on locality and climate [Davies 1988; CSIRO 1994]. Common house fly populations increase very rapidly in waste as the young maggots can emerge from eggs within a timeframe of 8 hours [CSIRO 1994]. In a properly kept vermicomposting bin, flies and cockroaches would not be found because of the nature of waste conversion, but snails could be found at times. All these insects, like the worms, take part in the decomposition of the waste materials and mineralisation process [Kostecka 2001].

5.6 Interactions of the different organisms

Vermicomposting could not progress without a host of microbes that degrade the waste materials. The decomposed waste and the microbes become the diet of the worms. A network or food chain of microorganisms is involved in the process of humification of biodegradable materials of plant and animal origin. In nature this occurs over a long time, while under the controlled environment of composting this is made to happen at a faster rate.

The importance of utilising these different organisms is in that, if waste materials are applied to the soil without proper degradation in the form of partly humified organic matter, the natural decomposition process will take place by the indigenous soil-dwelling micro-flora. This produces certain intermediate metabolites that in high quantities can hinder normal plant growth. In the competition for the available nutrients, the plants can fail due to the microbial competition. Composting degrades the organic material sufficiently over time so that it can be applied to soil in a stabilised form, avoiding these problems. Chemical composition of solid MSW and its biodegradable fraction is heterogeneous and composting mineralises most of the elements via partial humification [Darwin 1945; de Bertoldi *et al.* 1983; Haug 1993; Epstein 1997].

The food chain depicted in figure 5.4 shows the microbes as the most basic waste decomposers and a staple diet for higher organisms involved in the process. Bacteria, fungi and actinomycetes form the 1st degree consumers. This picture includes earthworms and certainother higher order creatures at the basic level, but they have been shown to consume the waste materials as well as the microorganisms [Haimi and Huhta 1986; Edwards 1988; Morgan 1988; Farrel 1997; Riggle 1998; Fraser-Quick 2002].

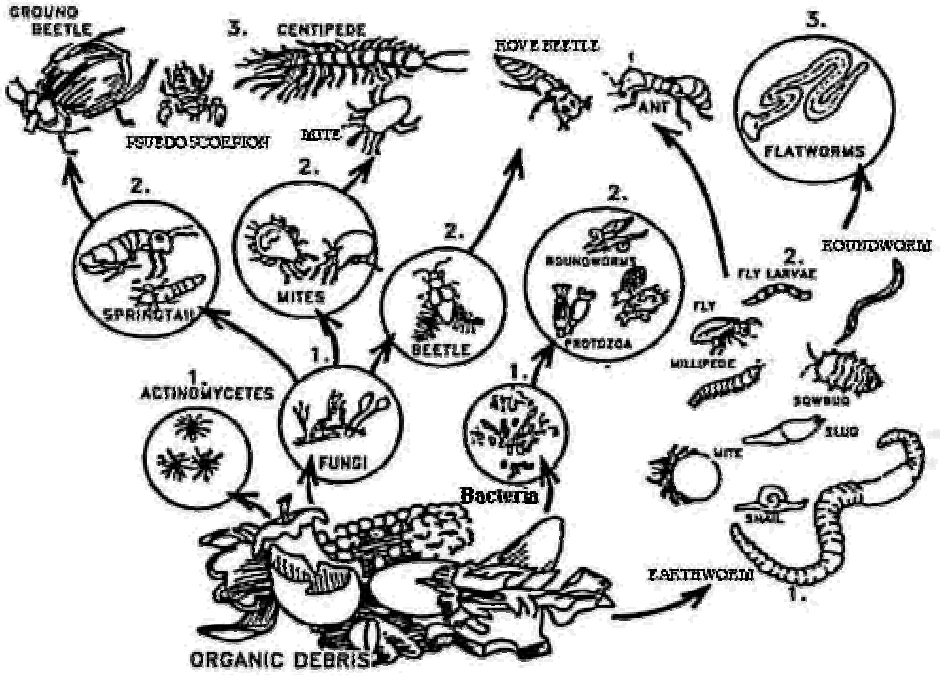

Figure 5.4 Food chain involved in composting process

[Ingham *et al.* 1985; Ingham 2000; van Zoest 2002]

More than 50 species of bacteria were isolated from the gut of *L. terrestris*, all of which have previously been identified to be present in fertile soil [Satchell 1983], their numbers being generally higher in the castings than in surrounding soil. Certain worm species such as *L. rubellus* show poor assimilative capacity towards N [Satchell 1983]. Certain algae and fungi, along with bacteria, are reported to be necessary dietary requirements for worms [Fraser-Quick 2002]. Cooke (1983) tested vegetative waste separately inoculated with *P. aeruginosa* and different fungal species and reported that worms seemed to prefer this over waste with less microbes. The author suspected this could be due to higher moisture levels or nutritional or palatability values introduced by the microorganisms [Cooke 1983]. It could also be due to higher microbial degradation [Jager *et al.* 2003].

Recent studies on interactions of red tiger worms, nematodes and microorganisms using cow manure and sewage sludge as substrate reveal that co-existence with the worms increases the numbers of fungivore nematodes and indigenous microbes in the material, while the initial population of bacterivore nematodes decreases [Dominguez *et al.* 2003].

Morgan (1988) tested the nutritional value of microorganisms to other creatures in the composting environment and speculated that the higher organisms such as worms were feeding off the microbes due to competition for the available nutrients. The presence of live microorganisms increased the growth rate of worms. *E.foetida* showed better growth when fed pure cultures of live microorganisms in the presence of four species of fungi, but negative results were seen with other organisms, possibly due to the antibiotics present or lack of diverse food source, or possibly as a result of some toxic metabolites produced by the micro-organisms. Earthworms utilise both microorganisms and simple nutrients available in substrate.

Worms have been known to contain certain fluids with antibacterial properties [Satchell 1983]. Earthworms could become infected by parasites and small insects. *Enterobacter aerogenes* is reportedly able to penetrate the intestines of many worm species and cause septicaemia [Rao *et al.* 1983]. Most human pathogens, such as *E. coli* get killed when consumed by composting worms. Competition between pathogenic organisms and indigenous microflora for nutrients in the worm castings has been shown to cause pathogen removal [Rouelle 1983; Allievi *et al.* 1986; Morgan 1988; Eastman 1999; Ellery 2000; Eastman *et al.* 2001; Sidhu *et al.* 2001].

Protozoa and nematodes prey upon microbes in the compost and soil. Some nematodes have been shown to be microbivorous (consuming both microflora and microfauna) [Frey *et al.* 1985]. Ingham *et.al.* (1985) pointed out that the bacterial-feeding nematodes increase the bacterial population in some studies and decrease in some, and speculated this might be specific to the nematode species and the rate of consumption. The authors failed to quantify it and identify the most favourable conditions and the effects in the matrix with other organisms. They speculated that of the bacteria that pass through the gut of the nematodes (like that of worms as well), approximately 60%, survived ingestion, some obtain an otherwise limiting nutrient, hormone or growth factor while in the gut, resulting in rapid growth after being excreted. These bacterivorous creatures cause transportation or spreading of the bacterial population within the substrate mass.

Earthworms are subjected to predation by terrestrial vertebrates (birds, amphibians, shrews and reptiles) as well as other parasites found within the decomposing matrix. Small red mites found in the vermicomposting bins sometimes attack the composting worms by consuming the live worm's body parts, after which the worm appears to have withered body segments [Slocum 2000b]. While predation from terrestrial vertebrates can be avoided by placing the vermicomposting matrix in a protected area (it needs to be protected from natural elements as well), predation from insects taking part in the process, such as red mites, can not be avoided entirely [Macdonald 1983; Ingham *et al.* 1985; Dowdle and Dowdle 2002; ROU 2002b]. Carnivorous behaviour of certain earthworm species has also been reported [Lavelle 1983a], as perhaps an evolutionary adaptation for available nutrition or for self-defence. Accidental ingestion of small worms by other larger worms is reported, in this paper,

to cause no harm to the small worm, as they emerge intact at the posterior end of the larger worm.

5.7 Conclusions

Many different microbial organisms such as bacteria, fungi, protozoa and nematodes take part in the degradation of organic waste materials. An understanding of the biology of the different organisms is important in studying a biological process like vermicomposting. In vermicomposting, different species of worms and insects graze on these microorganisms as well as directly consume the nutrients available in the waste materials. In considering a composting matrix as a small eco-system, the interactions between different organisms taking part in vermicomposting are important, as are the numbers of different organisms present.

Knowledge of the food chain involved in the vermicomposting process will help during the design as well as the operational stages of a blackwater composting system. High quantities of nutrients available in such a waste stream and these should be made available to different organisms decomposing the solid waste materials. Choice of the method of composting and the organisms used will influence the success of the process. Most organisms, such as microbes and insects, do not need to be introduced into a vermicomposting system, but the choice and stocking rate of worms is important. Data supporting this, available from the literature, will be analysed and reported in later chapters.

CHAPTER 6 SAFETY IN THE MANAGEMENT OF DOMESTIC WASTE AND WASTEWATER

6.1 Introduction

A most important aspect of managing domestic wastewater and solid waste that needs careful evaluation and assessment is human and environmental safety. In assessing the safety of a management system it is necessary to identify the level of risk to human health and environment, and conformance to regulatory standards and guidelines set by relevant authorities. Traditionally wastewater and solid waste management has required a person educated and trained in handling biohazardous materials, which has precluded the involvement of the general public. Such training becomes problematic for treatment systems installed at single households. Each household would need at least one person who is properly educated and trained in OHS and risk management issues, which is not possible for most communities. Minimum awareness has to be assumed when considering the communities' risk management capacity.

In this chapter, different aspects of risk management are reviewed within the context of residential blackwater and biowaste treatment by vermicomposting. Comparison is made between vermicomposting and the more traditional methods of blackwater management in developing countries, such as septic tanks and direct reuse. Relevant standards and guidelines that provide a pathway to optimise the risk management of vermicomposting system are discussed.

6.2 Risk management in domestic waste management

The Australia / New Zealand standard AS/NZS4360 defines risk as the chance of something happening that will have an impact on objectives. Covello and Merkhofer (1993, p.2) defined risk as "a characteristic of a situation or action wherein two or more outcomes are possible, the particular outcome that will occur is unknown and at least one of the possibilities is undesired". Risk relates to the probability or frequency of occurrence of a particular hazard or event, and some measure of the severity of its consequences. There can be positive or negative consequences of a risk [AS/NZS4360 1995]. The acceptability of the consequence of a hazardous event is a relative quantity (if it can be quantified) and depends on perception of the risk. A neighbour may not perceive a household blackwater treatment system as a risk. A voluntary risk may be adopted by the householder with a wastewater treatment system. Risk becomes acceptable with increased confidence in the operational safety of the system, given that the positive consequences outweigh the negative ones.

The hazards posed by an event can cause different exposure effects for different people [Ashford 1976]. Understanding the risks involved in a particular situation is important, and this can be done after a detailed risk assessment. Covello and Merkhofer (1993, p.3) explained the process of risk assessment as "a systematic process for describing and quantifying the risks associated with hazardous substances, processes, action or events". The term hazardous here could mean something that poses a hazard, physical, chemical or biological in nature.

Hazard identification for a risk management programme related to public health need not be done for each individual organism that posses a hazard, as comparison of risk over a range of organisms may be sufficient for proper risk management.

Probabilistic risk analysis is not easy for particular hazards, because sources of hazard and events cannot always be generalised across the different scenarios of risk evaluation. Nonetheless, risk can be expressed as a function of perceived hazard and frequency of exposure as:

$$\text{Risk} = f(\text{hazard, frequency}) \qquad \ldots 6.1$$

Community perception and acceptance becomes critical for the success of a community based wastewater treatment system that applies to individual households. Public awareness is key here, although this can be managed to some extent by education based on risk analysis studies. Community perception can be expressed as a function of calculated risk (using eq. 6.1 above) and public outrage:

$$\text{Community Perception} = f(\text{risk, outrage}) \qquad \ldots 6.2$$

It is important to note that risk needs to be minimized to raise community confidence so that the probability of community acceptance increases to the point that a wastewater treatment system at the residence level becomes acceptable and a common practice.

It is necessary to recognize the limitations of the technology. Maintenance is essential to the application of successful technology and yet it is usually forgotten. Any risk analysis should take account of maintenance scenarios.

Ideally the judgment of safety – or what is a tolerable risk in particular circumstances – should be defined specific to the affected community for the particular event. On a macro level, the final comparison among the benefit of any of the health-based targets, the acceptable levels of risk and the cost for achieving a certain level of risk management is for each country to decide [WHO 2003]. National and local guidelines on different safety aspects and risk mitigation measures are developed as a response to local or regional interests. Enforcement of regulations on waste management can be dependant on lifestyles and population [Pande and Grover 2000].

Risk calculation for projects that are relevant to public health usually is the responsibility of the designer or evaluator of the project, done prior to the system implementation. There is no significant history of community involvement in settling risk guidelines as part of the design process.

There are different qualitative methods of risk evaluation, such as the risk matrix table [AS/NZS4360 1995] or risk score calculator line diagrams [NSCA 1998, 2002]. There are more complex quantitative methods utilizing the power of statistics [Covello and Merkhofer 1993] and probabilistic theories [Kaplan 1991]. Different hazard scenarios will need to be analysed by different methods [Knief 1991; Knief *et al.* 1991]. Comparison of risks of blackwater composting with risks of other

decentralised treatment options of blackwater including currently employed septic tanks or direct application in agriculture or aquaculture require quantitative techniques.

Waste management involves risk ranging from those originating from mis-handling (spillage) and lack of monitoring (leakage) to those that are inherent (pathogenic). Risk evaluation applied to composting, should pay attention to the effect on the microbial life that could be both harmful (enteric pathogens) as well as eco-friendly (soil microbes). Composting and vermicomposting can not progress without beneficial microbial life, which takes an active part in the degradation of different waste materials through metabolism of the chemical constituents [Alcamo 2001].

6.3 Assessment and evaluation of risk for a residential waste management system

As detailed above, risk management can be described as a carefully structured attempt to eliminate losses, human, environmental or financial, caused either by an accident or forced outages [Joksimovich 1991] by carefully analysing or assessing the situation. Risk assessment for domestic wastewater management takes into account a risk source (e.g. blackwater), an exposure process (e.g. pathogens from contact) and a causal/consequence process (e.g. start and spread of a particular disease). The potential of the risk source to cause harm, the intensity and duration of exposure and the detailed connection between the exposure and consequences are important factors in risk assessment.

Risk characterization is done qualitatively, with acceptability of each risk evaluated based on the exposure level, frequency and consequences. A risk calculator matrix (Table 6.1) was adapted from the Risk Management Standard AS/NZS4360: 1995 for this study and includes both a technical approach, and for the areas where data are lacking, common-sense judgement. Low acceptability refers to high risk that needs to be averted, whereas good acceptability is 'tolerable risk' [Jaynes 2002].

Table 6.1. Qualitative risk evaluation matrix for the vermicomposting system (adapted from: [AS/NZS4360 1995])

Likelihood	Consequences or impacts				
	Insignificant	Minor	Moderate	Major	Catastrophic
Almost certain	S	S	H	H	V
Likely	M	S	S	H	V
Moderate	M	M	S	S	H
Unlikely but possible	L	L	M	S	H
Rare	L	L	M	M	S
Very rare	L	L	L	M	S

Risk level: V – very high; H – high; S – serious; M – medium; L – low / acceptable.

6.3.1 Hazards Identification and Risk Assessment

All the hazards originate from the nature of the raw substrate treated in the vermicomposting system, namely, blackwater and solid wastes. Blackwater offers health-related risks through the pathogen content that can cause diseases; garden organics offer hazards that arise from any sharp objects/sticks and dust; and kitchen waste contain putrescible waste that can attract vermin/ other animals with the potential of spreading the waste and can also undergo rapid deterioration giving off

noxious gases such as ammonia. These hazards will need an exposure process that can instigate the causal/consequence process towards the start of the disease.

The different hazards, exposure processes and an assessment of risk can be analysed on the basis of commonsense judgement and Table 6.1. For example, the hazard from treating human excreta can cause risk via handling and exposure and can have impacts on health due to the very high pathogen content and can attract public outrage due to aesthetics. The likelihood is high or 'likely', and consequences can be 'major', giving rise to a 'high' risk level. Hazards from treating animal waste can also be analysed the same way due to similarities with human waste.

Any sharp objects can cause cuts and injuries, coupled with the pathogenic content, causing infection. The likelihood is moderate but the impact can be catastrophic for the person involved, giving a risk level of 'high'.

Noxious fumes can have a likelihood of 'unlikely but possible' with an impact level of 'moderate', assuming low concentration, giving a risk level of 'medium. In the wet composting process, contamination to environment can occur if the system malfunctions such as leakage or spillage of wastes. Spillage is a common human error, therefore the exposure process is by handling, giving a causal process of groundwater contamination or spread of diseases from the pathogenic content in the waste handled. Likelihood can be moderate with major impact, giving a risk level of 'serious'.

Waste material can spread by vermin/rodents/birds only if the system is open. The likelihood is ‘rare’, but consequences can be ‘major’, due to the pathogenic content, the disease potential of vermin (“the black death”), and the risk to surface water pollution, giving a risk level of ‘medium’. Proper containment of the system can avert this hazard further.

Under normal circumstances, toxic materials/chemicals are not expected in a domestic waste stream, unless pesticides are accidentally included in the garden waste. This can cause worm-death to some extent within the vermicomposting unit, with likelihood of ‘unlikely but possible’ and an impact level of ‘moderate’, giving risk level at ‘medium’.

Food organics can deteriorate over time if not properly treated, but is ‘unlikely’ though the deterioration can cause ‘moderate’ problems of odour. A risk level of ‘low’ is expected. Garden organics can contain dust under dry weather, the handling of which can have ‘moderate’ likelihood and ‘minor’ impact for a person with normal health, but a significant impact on people with respiratory problems. This gives a ‘medium’ risk level. Table 6.2 presents the above discussion in a tabular format.

Table 6.2 Hazard Identification for the vermicomposting system

Hazard element	Source of risk	Risk Assessment
Pathogens in animal manure	Handling of animal manure	Risk is high, if manure is fresh. Pathogen can spread by contact and air
Human excreta	Handling and exposure	Risk is high as pathogen levels are extremely high. Pathogens can spread by air. Aesthetic considerations also important.
Sharps in substrate	Cuts and other injuries	Risk is high, as pathogen rich material is handled and infection pathways to the body are opened.
Noxious fumes	Gases	Risk is 'medium, as such fumes are not expected from compost or substrates and dispersion from the source is effective
Liquid contaminants	Improper handling	Risk is high of pathogenic leachate
Spread of substrate	Vermin or birds	Risk is medium, as project test box is situated covered, but uncovered boxes give rise to high levels of human risk
Toxic material	Handling or exposure	Risk is medium, as this project doesn't involve toxic chemicals.
Food organics	Deterioration over time	Risk low, only odour is a major concern.
Garden organics	Dust and odour	Risk medium-low, dust is the only problem.

Most of the risks associated with the vermicomposting unit can be reduced to acceptable levels by incorporating suitable safety measures such as basic personal protective equipments (dust mask, gloves, safety glasses etc), cleanliness and appropriate location. Observing the maximum possible safety levels can reduce the risk levels in an actual installation of the technology.

The acceptability of a particular risk depends on the level of the risk. Proper monitoring and maintenance of the vermicomposting system can avert most of the hazards related to system performance, such as leakage of liquids and spread of

waste by vermin. The location of the system can be important in avoiding vermin and birds. Safe transportation of waste to the system is important, and should be undertaken by responsible people. Containers for temporary storage and transportation of waste to the system, if required (solid wastes), should be dedicated to the task. Plumbing for liquid waste transportation should be properly monitored. Table 6.3 presents the risk management strategies.

Table 6.3 Risk management of vermicomposting system for an experimental set-up (not an operational community system)

Risk	Acceptability	Management
Pathogens in blackwater	Very low	Adequate preventive shots for all personnel who come in contact with the area. Installation of biohazard signs. Use protective equipment, gloves, masks etc while handling the substance.
Potential toxins in the compost	Medium	Wear protective clothing, minimum of gloves, safety glasses and face mask
Potential contaminants in the liquids	Low	Use containers that are adequately marked and not used for other purposes without proper washing Wear protective clothing, minimum of gloves, safety glasses and face masks
Potential injuries from sharp sticks in the compost	Very low	Wear suitable heavy duty gloves Handle materials with tongs, shovels and other scoopers
Noxious fumes	Medium	Unlikely in composting systems, but ensure adequate ventilation
Vermin	Medium	Keep lids on containers or ensure that all access for animals are blocked. Check environs of experiment before entering site.
Body contact	Very low	Wash hands after each operation. Wash any body part that may have come in contact with liquids or solids
Leachate	Medium	Leachate has medium-level contamination. Wear gloves and eye protection. Routine testing recommended for pathogens.
Food material	High	All waste food to be transported in closed containers (buckets with lids). Food waste not to be handled unless with gloves and suitable clothing. All food waste that is excess is to be disposed of in appropriate garbage tins, wrapped in plastic or glad wrap.

6.3.2 Advantages of the vermicomposting system – comparison with direct application of nightsoil in agriculture/aquaculture

The practice of direct reuse of nightsoil/blackwater in agriculture and aquaculture has been identified in the literature [Pescod 1992; Aalbers 1999; Sophin 1999]. Many studies have been conducted on the safety aspects of this, though the results of such studies can have minimal impact on the rural population that engage in such activities on a routine basis, as it is a culturally accepted practice. Proper treatment of such waste before reuse can only improve the associated risks. A comparison of direct reuse of blackwater/nightsoil in agri/aqua-culture and vermicomposting of domestic waste is presented in the following.

In the analysis of vermicomposting system it is found that most significant risk can be avoided by proper maintenance of the system and taking care of the basic personal safety issues such as use of personal protective equipment (gloves, dust mask and proper footwear). The discussion in the previous section is summarised in table 6.4 for comparison with direct blackwater application in agriculture and aquaculture. As expected, the direct application of nightsoil/blackwater to crops and fishponds posed high risk in most of the identified events as possible sources of disease spread compared to medium to acceptable low levels for the vermicompost.

Table 6.4 Risk evaluation for domestic vermicomposting of blackwater and biowaste - best-case scenario (regular monitoring and proper operation):

Hazard	Likelihood	Impact	Risk
Cuts and injuries from sharps in the solid waste (use of PPE)	Moderate	Major	Serious
Start of disease from contact with blackwater (use of PPE, no contact)	Unlikely	Major	Serious
Spread of disease after one householder is infected (immediate medical attention)	Moderate	Major	Serious
Effluent leakage from raw blackwater storage (monitoring and timely repair)	Rare	Moderate	Medium
Treated effluent leakage from the system (monitoring and timely repair)	Rare	Minor	Low
Disease caused from contact with compost	Very rare	Minor	Low
Children getting infected from the system (fencing)	Very rare	Major	Medium
Spread of waste material by pets or other vectors (fencing, location)	Unlikely	Minor	Low
Plant diseases from use of compost	Very rare	Moderate	Low
Environmental degradation from use of compost	Very rare	Minor	Low
Foul odours from the system (monitoring)	Unlikely	Moderate	Medium
Worm casualty from overstocking of waste or flooding with blackwater (monitoring)	Rare	Minor	Low
System failure due to weather patterns (location, monitoring)	Rare	Moderate	Medium

As evident, the proper treatment of blackwater and biohazardous waste materials reduces most of the risk to acceptable levels. On the contrary, similar analysis on the direct reuse of blackwater/nightsoil in agriculture and aquaculture provides a different picture. Certain hazards could appear to come from different sources, such as cuts and injuries from use of equipments like a shovel in handling the raw waste material. The likelihood is moderate, though impact can be major due to the pathogens contained, giving serious risk level. As nightsoil is handled manually, disease from contact with the material is almost certain with major impact on health,

giving high risk. Spread of disease is likely with major consequence and poses high risk.

Raw blackwater, as applied to fields or ponds, can affect groundwater and surface waterways almost certainly with major to catastrophic impacts on environmental and human health. These therefore have high to very high risk levels. As the waste is applied without much treatment, pathogenic effects on farm plants and fish are likely with a major impact posing high to very high risk. Disease caused by contact with plants and fish can be moderate possibly causing major impacts. This is estimated at serious risk levels.

As the waste material is spread in open area, drinking of infected water or spread of the infected materials by animals or is almost likely with possible catastrophic impact on the environment and humans and animals around. This poses very high risk in the case of direct excreta use in farming and fish culture. Plant diseases are likely with moderate impact on people who depend on them.

The likelihood of soil degradation is only moderate, as the nightsoil is organic in nature, and can have minor impacts (disregarding pathogenic effects that are analysed separately). This has medium risk level. But due to the nature of the waste material, foul odours is almost certain with moderately adverse aesthetic consequences. This has high risk on public acceptance. Effect of weather in spreading the waste is almost certain with possible catastrophic consequences leading to many other mentioned hazards such as disease, and this has to be dealt with as a very high risk issue. The above discussion can be presented in tabular form:

Table 6.5 Risk evaluation for direct application of nightsoil in agriculture/aquaculture

Hazard	*Likelihood*	*Impact*	*Risk*
Cuts and injuries from sharps while handling raw solid material (shovel etc)	Moderate	Major	Serious
Start of disease from contact with blackwater/nightsoil	Almost certain	Major	High
Spread of disease after one householder is infected	Likely	Major	High
Raw blackwater affecting groundwater	Almost certain	Major	High
Raw blackwater affecting waterways	Almost certain	Catastrophic	Very high
Pathogenic effect on edible crops	Likely	Major	High
Infection from ingestion of affected fish/crops	Likely	Catastrophic	Very high
Disease caused from contact with affected plants/fish	Moderate	Major	Serious
Spread of infected waste material by pets or other vectors	Almost certain	Catastrophic	Very high
Plant diseases	Likely	Moderate	Serious
Soil degradation	Moderate	Minor	Medium
Foul odours	Almost certain	Moderate	High
Infections to other flora/fauna	Likely	Major	High
Spread of nightsoil due to storm/rain	Almost certain	Catastrophic	Very high

6.3.3 Comparison with septic tank treatment option - risk score calculator technique

In most developing countries and rural areas, the most-preferred sewage treatment option is that of septic tanks [Barwise 1904; Netter *et al.* 1993; AS/NZS1546.1 1998; Boyden and Robilliard 2001; Kenway *et al.* 2001]. These provide slow treatment to satisfactory standards and are much safer compared to direct reuse of nightsoil in fields and fish-ponds, but with no recovery of any valuable ingredients in the waste

such as nutrients. On the other hand, vermicomposting of blackwater can retrieve most of the nutrients, if not all, for return to the surface nutrient cycle.

A qualitative analysis of different scenarios based on the risk matrix in Table 6.1 would take much time and effort. A different technique, the risk score calculator scales [NSCA 1998, 2002] can include a number of scenarios for each hazard in one graph and give more accurate risk levels that can be adopted for either qualitative or quantitative analysis. Analysis of different scenarios and different hazards could be included in a single graph, within readability constraints. Another advantage for this technique is its pictorial representation of the analysis.

The NSCA risk score calculator scales are used to compare the risk of the three treatments, vermicomposting, direct application and septic tanks. Fig 6.1 shows risks associated with the effluent from vermicomposting systems causing environmental pollution by affecting surface/ground water. The probability of any leakage affecting the groundwater or surface waterways is rare, as the design of the system will contain any liquids. As such, the exposure level will be infrequent. The point on the tie line where the line connecting these two points can be connected to the relevant consequence level, that of moderate. The line is then extended to calculate the risk level, which in this case is below medium.

In direct application of nightsoil to farms/ponds, pollution of ground/surface water is very likely, the application can be between occasional and frequent. The line connecting these points and impact level of moderate to major gives very high risk score. In the case of septic tanks, the likely probability and occasional exposure to

the environment, together with minor impact level (due to the treatment received in the tank) gives a high risk score.

Fig 6.2 shows risk of disease caused by direct contact with pathogenic blackwater/nightsoil. Depending on the system maintenance, probability of contact can be unlikely to moderate with possible serious consequences, giving a risk score close to 'serious'. For the direct reuse option, the probability of contact is very likely, with occasional exposure (assuming some level of personal protection is observed). The consequence can be major, giving very high risk score. For septic tanks, probability contact and exposure level are both rare, with important serious consequence (if happened), giving low risk.

Fig 6.3 shows risks associated with disease caused by effluent. Here, the final effluent is of more concern and in direct application of nightsoil has no treated effluent. But for uniformity, the treatment it receives in field is considered, and its effect on populations, as affected from infected plants/fish is considered. The analysis shows a medium to low risk score for both vermicomposting and septic tanks options due to the high level of treatment offered in these two techniques, while direct reuse has very high risk due to lack of proper treatment of effluent.

The risk scores given by both techniques - that of risk matrix and the risk calculator - are similar, though not exactly same. In the calculator inputs include probability of the risk and exposure level (of an individual or the environment). This comparative risk study shows that direct application of human waste in agriculture and aquaculture should be avoided and better treatment options sought. In

vermicomposting, the waste materials are safely converted into soil amendment material with reduced levels of pathogens and could be of use in agriculture. Providing a safe decentralised waste treatment system for blackwater and biodegradable waste could be of use in places where centralised or other waste management facilities are unavailable.

From an agricultural point of view, the risk of nutrient loss from available fertiliser/soil conditioner material is important. Harvesting of worms as a protein source in fish culture has been in practice in many places, and this could be an application of vermicomposting in aquaculture. The water effluent from the vermicomposting unit could be further treated and utilised in irrigation or other uses. Proper treatment of this effluent along with greywater from the household could offer a source of recycled water for different uses at the household, without health implications.

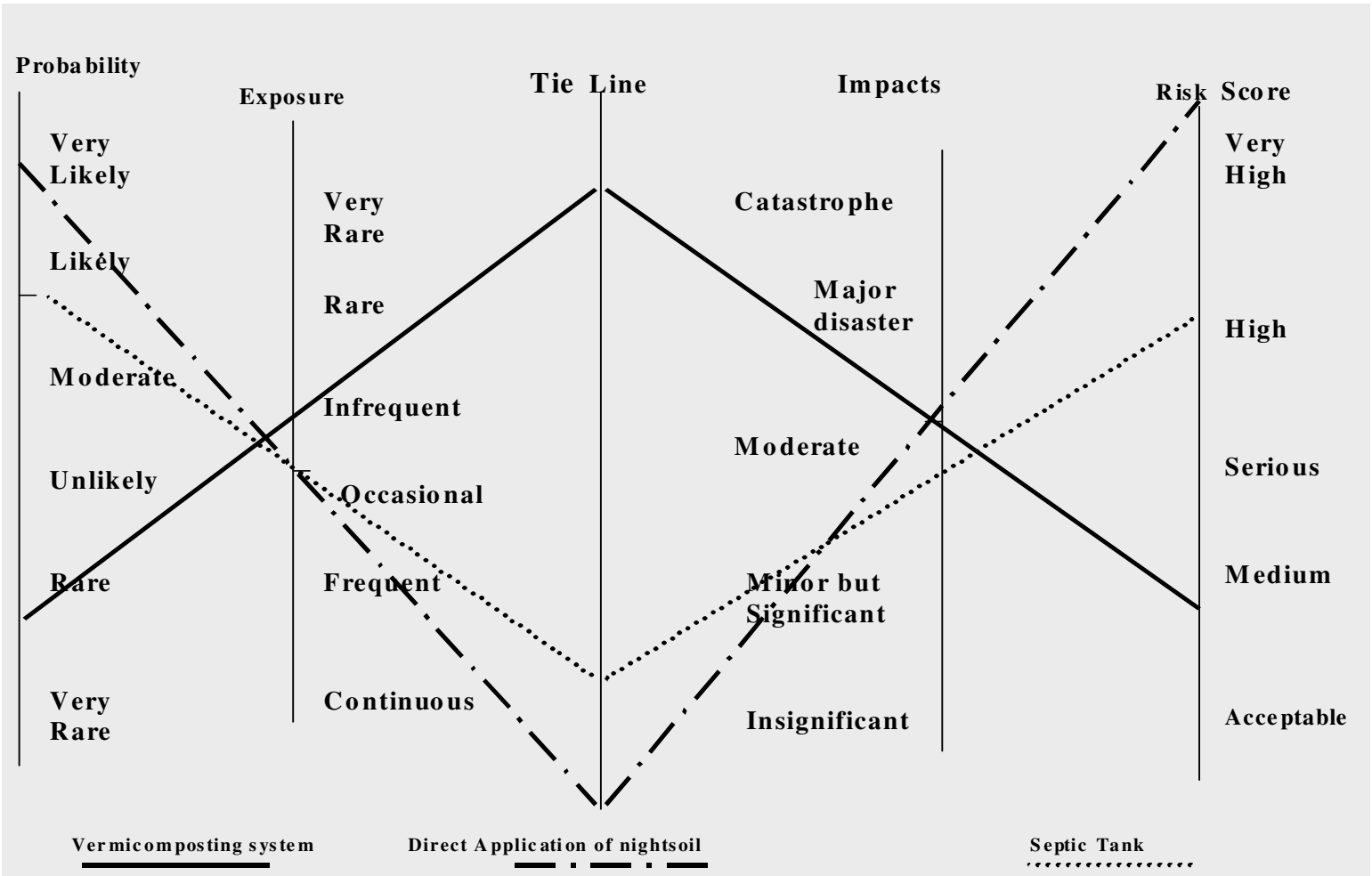

Figure 6.1 Risk calculator diagram for surface/ground water pollution from effluents

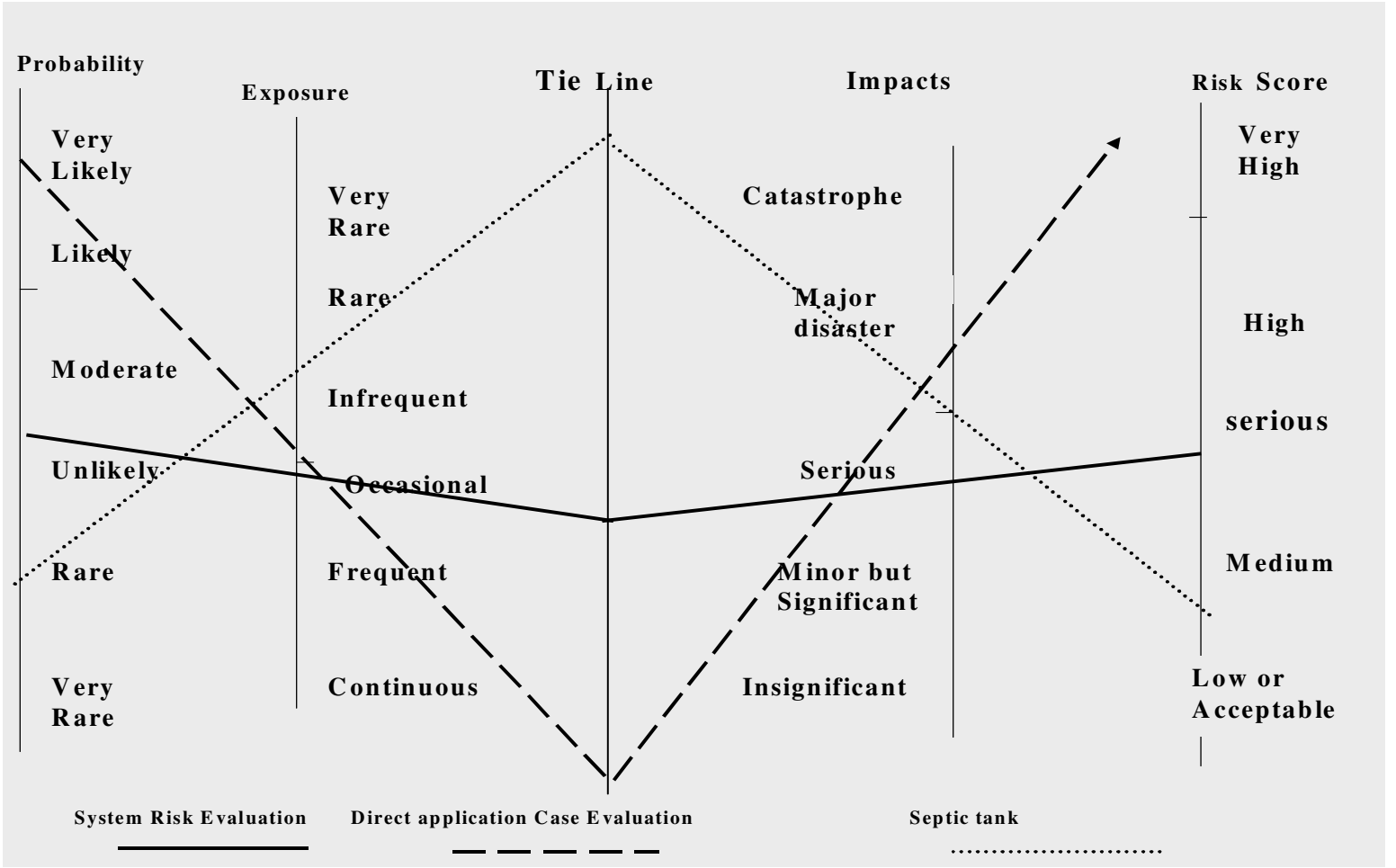

Figure 6.2 Risk calculator for disease-caused by contact with blackwater

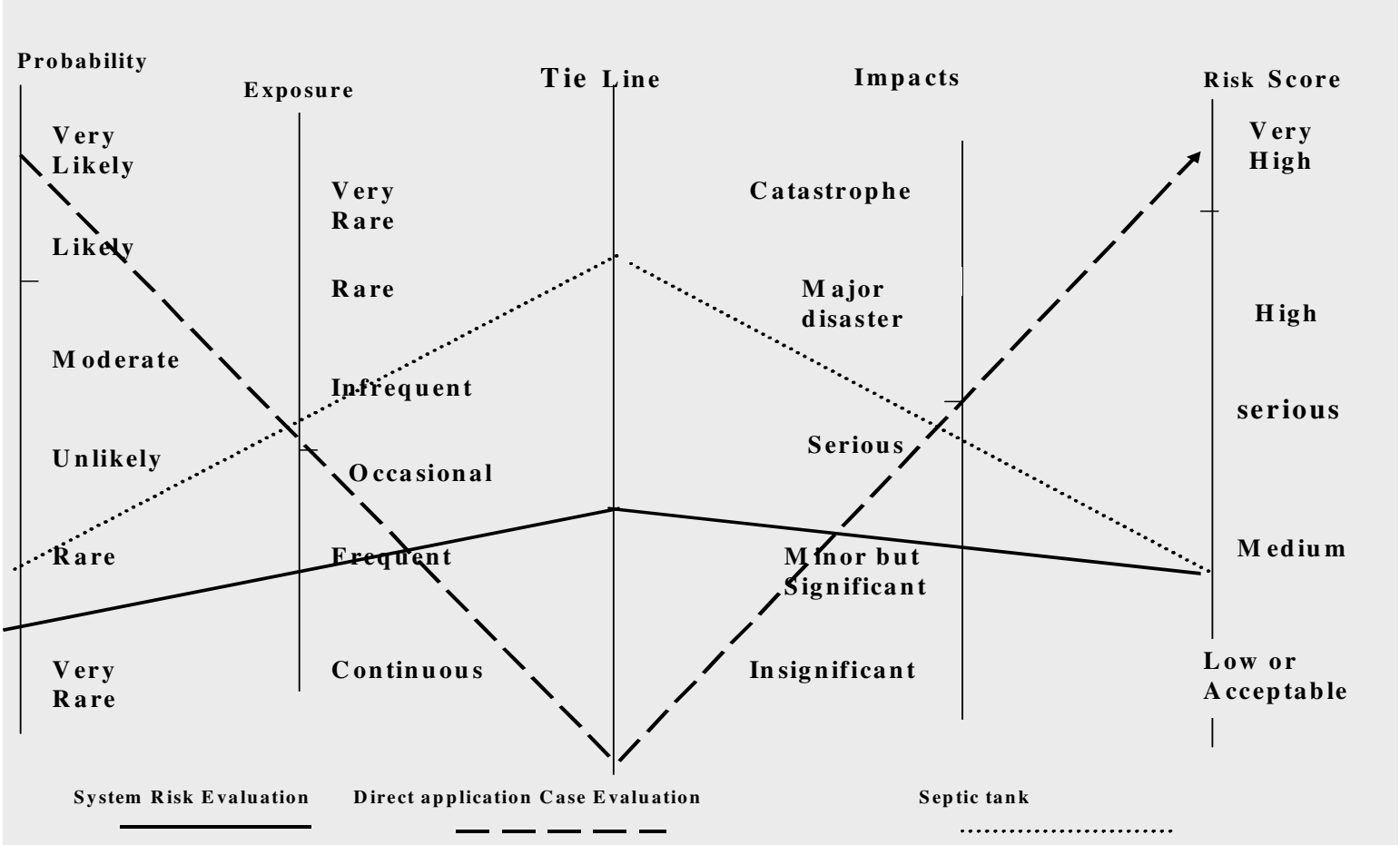

Figure 6.3 Risk evaluation for disease caused from effluent

(As treated by vermicomposting system, effects from infected plants/fish and effluent from septic tanks)

6.4 Risk Assessment of a Working Prototype Vermicomposting Unit

To test the hypothesis of this thesis, an experimental prototype of a vermicomposting unit was designed and tested. Details of the Vermicomposting unit are presented in Chapter 8. This section is concerned with the risk analysis of the conceptual design. Prior to starting the tests, a risk assessment was conducted for approval from the Institutional Biosafety and Radiation Safety Committee at the University of Western Sydney as part of Occupational Health and Safety requirements.

The vermicomposting unit was designed for waste generation from a single household and for vermicomposting of blackwater and biodegradable waste. Due to the unavailability and health issues of blackwater for test purposes, fresh pig manure is selected based on its comparable characteristics [Aalbers 1999; Sophin 1999; Envirocycle 2002; Yang *et al.* 2002]. Fresh pig manure was obtained from the University of Sydney Camden Pig Research Farms, which were approximately 40 km from UWS, so the risks involved in transporting the material from the source to the usage point was analysed, along with risks involved in the treatment at the UWS site.

As per the literature cited above, pig manure contains a comparable number of pathogens and nutrients to human sewage. Collection, transportation and treatment of pig manure for the project involves hazards mainly related to pathogenic content of the manure. The exposure process can include splashing of the waste to hands, face and feet, splashing/spillage/leakage from the container while transporting in a truck, spillage or leakage during connection of the tubes to the treatment system, leakage due to loose connections at a later stage and aerial transport of pathogens while

opening the container for stirring (for homogenisation). The risk levels are estimated based on the risk matrix discussed earlier (Table 6.1). Most of the hazards are relevant to operators only, but hazards identified at the treatment point can affect any visitors to the facility.

The likelihood of pathogens coming in contact with personnel by splashing at collection is likely, with major possible consequences. This is estimated to have a high risk level. Splashing while in transit is moderately possible, with only minor consequences as the container is not near personnel in the truck. This has medium risk level. Observation of existing risk management and safety procedures at the Camden pig farms were observed. Spillage or leakage from the container while handling at collection or transportation can have moderate likelihood with major consequences for people handling the container, giving a serious level of risk. Safety measures such as personal protective equipments (gloves, goggles, facemasks and proper clothing) and operating in a well-ventilated area can reduce the risk in all cases. Properly securing the container with a tight lid to the truck reduces risks during transport.

The tubes through which the liquid flows into the vermicomposting unit are connected manually to the filled container at the test point. Leakage of liquid from loose connections, split ends or breakage of the tubes or connectors has a moderate likelihood and major consequences due to pathogenic waste material. This gives a serious risk level for this event. Risk management involves checking the equipment, using gloves at all times, wearing proper clothing, operating in well-lit areas and having proper vaccinations.

Figure 6.4 The test site was fenced and safety warnings installed.

Aerial dispersion of pathogens from the pig manure at collection, in transit and at the treatment point (during stirring for homogenisation) has the likelihood of 'likely', 'rare' and 'likely' respectively with major consequences. This gave risk levels of high to medium. Observation of personal safety including proper handling and usage of PPE such as gloves, dust/gas masks and goggles becomes a "must" to avert this risk. Visitors to the experimental facility have to be properly briefed about the risks involved. Tables 6.6 and 6.7 summarise the above discussion.

Table 6.6 Hazard identification: for operators as well as visitors

Hazard Element	*Exposure Process*	*Risk level*
Pathogens at collection	Splashing at collection	High
Pathogens in transit	Splashing in transportation	Medium
Container	Spillage or leakage of sewage	Serious
Tubes at usage point	Loose connection, leakage, breakage	Serious
Pathogens at collection	Aerial dispersion	High
Pathogens – transportation	Aerial dispersion due to liquid movement in the container	Medium
Pathogen at treatment point	Aerial dispersion while opening the container	High

Table 6.7 Risk management

Risk	Acceptability	Management
Pathogen spreading at collection via contact or air	Very low	Existing management measures at Camden research facility.
Pathogen spreading during transportation	Medium	The container to be secured to the vehicle, lid fastened properly and the container covered.
Pathogen contact at usage point	Low	Personnel handling the manure to avoid contact at all times. Safety equipments to be used at all times.
Risk of disease to visitors	Low	The area used for tests to be fenced, safety and biohazard sign boards installed. Visitors should be informed of risks and safety.
Risk of disease to operators	Very low	Therefore safety equipments to be worn at all times during tests and sampling. Adequate preventive measures such as vaccines to be taken, with all required booster doses.
Contact at time of sampling can cause risk of diseases	Very low	Personnel taking samples to take care of safety and preventive measures. This is relevant to people working on other projects in the area.
Pathogen spread via air or other vectors	Low	Containers to be kept closed with tight lid and inaccessible to rodents, at no point should the substance be open to wind.

6.5 Conclusions

Assessment and proper management of risks emanating from handling and treatment of blackwater and biodegradable waste is very important, even more so regarding domestic waste treatment systems. The level of risk depends on the nature and extent of the hazard, as well as the frequency of exposure. Success of any onsite treatment system depends on public acceptance, and this can happen only if awareness is created about the safety aspects of using the system.

A qualitative risk evaluation was conducted on different aspects of domestic waste management and in vermicomposting. A comparative risk study with treatment

options for blackwater of direct reuse in farming and septic tanks showed that vermicomposting has a lower level of risk.

Untreated sewage, as applied to farms and fish-ponds, poses very high risk to the people and environment. Established decentralised treatment by septic tanks is comparable in most risk levels with the vermicomposting of blackwater and solid wastes, with the latter having an additional advantage of producing a safe solid residue that can be used as a soil conditioner. Vermicomposting can be beneficial in farming for the by-products such as compost in agriculture and live worms as protein sources for aquaculture, with reduced risks.

Finally, it was shown that by observing personal safety procedures and proper maintenance of a prototype vermicomposting unit most of the identified hazards could be averted. Awareness is a key in maintaining a low level of risk for a vermicomposting waste management system in a household.

CHAPTER 7 TRIALS OF VERMICOMPOSTING AND MICROBIAL ACTION – TESTS FOR THE DESIGN OF THE WASTE MANAGEMENT SYSTEM

7.1 Introduction

The literature suggests that the higher the worm stocking rate for vermicomposting, the better the chances of a good process [ROU 2002b]. This suggestion was tested with severe organic shock and varying substrates in a series of vermiculture tests. This chapter discusses the methodologies and findings of these tests. The tests presented in this chapter were designed to validate data given by ROU (2001) and identify the best conditions to optimise the design of blackwater-blackwaste co-composting system at residential level.

The vermiculture tests were done in two phases – a second phase was required because the first phase did not give the expected results. Microbial composting was conducted separately to create semi-degraded materials as a starting substrate for later projects and also to check the progress of microbial composting with limited quantities of materials.

The vermiculture tests were routinely monitored for temperature within the mass undergoing worm action, pH of the leachate and the soluble extract of waste input and the final castings, weight and volume reduction between the start and end of the composting cycle and moisture content of the input waste and the composting mass.

These initial tests were instrumental in the final design of the prototype, the testing of which is reported in Chapters 8 through to 10.

7.2 Phase 1 Multiple Substrate Vermiculture Tests

The objective of these tests was to establish a self-sustaining worm population for use in blackwater-biowaste vermicomposting experiments, to validate results reported in the literature and to assess the performance and survival rate of the worms at different initial conditions in terms of the processing capacity (ultimate processing rate without causing system failure).

7.2.1 Materials and Methods

A mix of red wiggler, tiger worms and red worms was purchased from Eagle Creek worm farm, Nana Glenn, NSW; and were grown in a mix of waste materials in plastic boxes with dimensions 450mm * 450mm * 300mm. Residential wastes were simulated with measured quantities of garden waste procured at source and food wastes from the University cafeteria at Werrington South site.

Initially, eight different boxes were set up with different waste compositions and worm stocking rates (Table 7.1). The terms ‘high’ and ‘low’ as used in the table are explained in section 7.2.2. The tests were designed to optimise the worm action with varying conditions such as worm biomass and different substrate conditions.

A high worm biomass suggested by research [ROU 2002b] is within the range 10-12 kg/m^2. A loading of 10 kg/m^2 was adopted based on advice from the worm farmer [Dowdle and Dowdle 2002]. A low biomass was assumed to be less than half of high (approximately 4 kg/m^2).

Table 7.1. Multiple container vermiculture configurations

#	*Worms loading*	*Food Organics*	*Garden Organics*
1	High	High	High
2	High	High	Low
3	High	Low	High
4	High	Low	Low
5	Low	High	High
6	Low	High	Low
7	Low	Low	High
8	Low	Low	Low

The different breeds in the worm mix, as per data given by the worm farm, were Red Tiger worm (*Eisenia andrei*) and Red Wiggler worm (*E. fetida*) approximately 80%, Indian Blue worm (*Perionyx excavatus*) approximately 19.5% and the remaining portion as local Camphor creek worm (prolific in summer, less in winter). Their mature vermicastings was used as bedding in the boxes [Dowdle and Dowdle 2002].

The parameters used to assess the success of breeding and composting in this trial were:

- Compost temperature achieved during worm action
- Moisture content
- The pH and quantity of leachate
- Behaviour of worms in the mass as related to the amount of worms (live weight)
- Weight and volume reduction of substrate added (over a given period of time which was to be assessed as part of the experiment).

The first two parameters are important because worms are highly responsive to wide fluctuations in temperature and the humidity of the matrix. The cooling effect produced by removal of excessive moisture could dampen a temperature rise in the system. Moreover, higher temperatures could lead to worm mortality and higher microbial action. A long-stem methanol-in-bulb thermometer and a bimetallic thermometer were used for the temperature measurement. Moisture content was determined by oven drying a representative sample taken from the centre of the matrices. The pH of leachate was important due to the fact that this could be an indicator of the pH of the composting matrix itself; and this was measured using pH meter from Envirosensors 40603, according to the Standard Methods [Clesceri 1999].

Behaviour of worms was based on worm activity, establishing whether they were climbing up the walls of the boxes, or wiggling through the top of the waste and how many were dead (no movement, degraded bodies). The live weight of worms, at the end of the tests, was measured by harvesting the worms (manually separating them from the substrate/castings) by spreading the whole material on a flat surface evenly in light so that they crawl under, then removing the castings and collecting the worms. If this was not possible, handpicking was used.

7.2.2 Experimental Procedure:

Eight Plastic boxes of approximately 300mm depth (optimum composting bed depth for test beds [ROU 2002a, 2002b]) and 0.20 m^2 surface area at top were used. The worm biomass in half the boxes was the optimum 10 kg/m^2 and the other half, 4 kg/m^2. For the tests, this translated into 2 kg for high worm stocking rate and 0.8 kg

for the low worm-stocking rate. The boxes were covered and sheltered against light and weather as well as predators. The boxes were labelled as per the test conditions and placed on blocks, high enough to collect the leachate.

A thin layer (approx. 25 mm) of inert material such as wood chips was put at the bottom to allow drainage of leachate. This also allowed cool conditions within the box and a passage for air at the bottom. A 50 mm thick layer of mature compost material was laid with the worms (the castings in which the worms arrived were used).

The wet weight of food waste and garden organics was determined. The substrate contained 60% food waste and 30% garden organics with the remaining portion of amendment materials (shredded paper/card board). This composition was decided based on data from studies elsewhere [Haimi and Huhta 1986; Appelhof 1988; Dominguez *et al.* 1997; Riggle 1998; ROU 2002b]. A sample of waste materials was examined for dry weight to assess the amount of moisture and whether more water was required.

Based on literature that suggests worms eat half their body weight per day under favourable conditions [Haimi and Huhta 1986; Appelhof 1988; Dominguez *et al.* 1997; Riggle 1998; ROU 2002b] it was estimated that nearly 800 grams of wet weight waste material (including 500gm food waste and 250 gm garden organics with 50 gm paper) needed to be added to the high worm content (1.6 kg worm) boxes per day when the composting was proceeding at a stable rate. The materials for the low worm content boxes weighed 300 gm, comprising of approximately 180 gm and

90 gm of food and garden waste, respectively, with 30 gm paper shreds. More substrate was added just before holidays and weekends for stock.

It was determined to suspend addition of new substrate until the system regained stable processing levels if the worms did not reduce the substrate at the expected rate. It was decided to estimate the % w/w (wet) of each type of waste, so that %w/w moisture added can be evaluated and compared with amount of leachate produced. Every day the volume of leachate produced was measured, as was the pH. If the amount of leachate was too small, pH was measured when the leachate volume was sufficient. Temperature was measured twice daily by inserting a long-stem thermometer into the substrate perpendicularly, but care was taken not to insert it down to the bottom. Worm action, such as whether they were trying to escape by climbing up the wall of the boxes and the numbers at the top of the composting mass was noted. The tests were supposed to end when the boxes or the experiment failed.

7.2.3 Occupational Health and Safety

Though composting of the chosen substrates did not warrant any major concern for health issues, it was decided to conduct a risk study on the different aspects. This was done as part of the preparation of the application for approval from the University's Institutional Biosafety and Radiation Safety Committee for this and future projects. Though this vermiculture tests did not involve any pathogenic materials, hazards such as injury to the personnel from sharp items or sticks in the composting material and dust in the dry garden waste were considered. A risk management table was formulated (Table 7.2) and the safety protocol was developed as below. The

occupational safety checks and protective measures were taken on a daily basis in dealing with the composting system.

Table 7.2. Risk Management for the vermiculture tests

Risk	Management
Potential toxins in the compost	Wear protective clothing, a minimum of gloves, safety glasses and face mask
Potential contaminants in the liquids	Use containers that are adequately marked and not used for other purposes without washing properly. Wear protective clothing, minimum of gloves, safety glasses and facemasks.
Potential penetrating injuries from sharp sticks in the compost	Wear suitable heavy-duty gloves. Handle materials with tongs, shovels and other scoopers as appropriate (as not to cause injury to worms also).
Noxious fumes	Unlikely in composting systems, but adequate ventilation should be ensured.
Vermin, Disease vectors	Keep lids on containers or ensure that all access for animals are blocked. Check environs of experiment before entering site.
Body contact	Wash hands after each operation Wash any body part that may have come in contact with liquids or solids
Leachate	Leachate has low-level contamination. Wear gloves and eye protection
Food material	Waste food can deteriorate if stored for a long period without refrigeration. All waste food to be transported in closed containers (buckets with lids). Food waste not to be handled unless with gloves and suitable clothing. All food waste that is excess is to be disposed of in appropriate garbage bins, wrapped in plastic or glad wrap.

Safety Protocol:

- No waste material should come in direct contact with the personnel handling the waste and worms.
- Use safety glasses, facemask, gloves, proper footwear and lab coats.
- Care should be taken while handling the leachate.

- Leachate is of comparable quality to compost tea, which is a fertiliser. So no threat to the environment is expected.
- Do not deal with waste materials if the person is sick.
- For transportation of food waste from cafeteria, assistance of technical officer to be sought.

7.2.4 Observations, Results and Inferences

The final worm biomass in all the boxes was approximately 700gm, which is 7.3% of the initial 9.6 kg. Individual boxes were not measured separately as there was a high loss due to worm migration and mortality. As early as day 2 of the experiment, it was noted that the worms were trying to escape from the boxes and even climb up the walls of the large container in which the boxes were placed. Wet weather might have been one cause for this, as the waste substrate was drier than the humidity-saturated air outside. Another possible reason was the material in which the worms were housed. The initial bedding given to them also was probably not deep enough [Dowdle and Dowdle 2002].

During the following days most of the garden waste and paper shreds remained untouched and the food waste had attracted fungi. Fungi grow under conditions drier than that favoured by bacteria and worms. Certain fungi have been reported to be toxic to the worms [Tortora *et al.* 1998].

A review of the experiment suggested the garden mulch added in the bedding should have been finer (it was added as leaves and small branches), and the paper shreds

should have been smaller (it was added in long strips). This would have allowed the moisture to be captured and retained longer, making the temperature and moisture content optimum for the worms [Dowdle and Dowdle 2002]. The reason for the substrate not turning anaerobic even during the prolonged inaction of worms could be traced to dryness. Advice was that the initial bedding is best if made up of old worm castings or mature and damp cow/horse manure or damp coconut fibre, with the amount of moisture at 70% [Fraser-Quick 2002]. A field-test for correct moisture level is to slightly squeeze the material for any presence of water droplets - the "farmer's fist" method.

The bedding should be at least 10cms thick. Garden mulch and paper shreds could also be added, but it was recommended to use a mechanical mulcher to reduce the particle size to degrade tougher parts in the substrate that worms and microbes find difficult to deal with [Haddon 1993]. Such preparation would be necessary at the start, until the worm population has been established and the microbial population in the substrate is strong enough to keep degradation progressing.

It was considered best to add food waste in the form of strips on top of the matrix within the box, instead of an even spread. This would allow the worms to retreat from the new material and return to it when they were comfortable with it. The pH of the food waste added was important; if the pH is too high or too low, the worms would try to escape from that area [Edwards 1988; Aranda *et al.* 1999]. It was recommended to add small fragments of food waste for a start and to monitor the contents over time [Dowdle and Dowdle 2002].

The objectives of the tests were not being successfully met in any of the eight test boxes and the experiment was abandoned. The high rate of worm mortality and lack of evidence of proper composting required that certain revisions be made to the experimental procedure.

7.3 Single Substrate Vermiculture Tests

The objective of this test was to validate the suggestions for the failure of the initial vermiculture tests, to establish a self-sustaining worm population for use in blackwater-biowaste vermicomposting experiments, to validate results available in literature and to investigate the responses of a mix of different breeds of composting worms to a mixed residential waste substrate. This experiment was considered as phase 2 of the vermiculture test.

7.3.1 Materials and Methods

This time, only one box was used, as the main purpose of the test was to check if the inferences were true for the earlier project's failure. Suitable material for bedding was procured and prepared. Recommended materials included mature cow manure, mature horse manure and mature vermicastings to be mixed with fine garden waste and paper shreds as bulking materials. The garden waste and paper shreds in the bedding were approximately 10 % v/v with moisture content of approximately 65% [Dowdle and Dowdle 2002; ROU 2002b].

The test box was filled to 10cm depth with nearly 3kg bedding material. Care was taken to ensure the moisture content of the bedding was adequate (65%) for the

worm population. The box was tightly closed so that worms could not escape during wet weather. For adequate ventilation, small holes were created on the sides of the box with a hand-drill for air passage and placing a suitable size cardboard on top as a lid. The box was protected from light, heat, predators and excessive vibrations.

All the worms remaining alive in the boxes from the earlier test were harvested and biomass determined. As the worm biomass (approximately 700gm) was less than that required for the high-rate loading (1600gm), additional worms were purchased from the same worm farm as in the first phase of the experiment. Upon application in the new box, the worms were seen to sink into the bedding. The addition of new substrate could be started within a day.

A mix of food waste, garden organics and paper shreds (30-33, 60-66 and 10-1 %w/w respectively) was placed in strips or rows on top of the bedding, or randomly placed; but care was exercised not to put the waste materials in large heaps that covered the surface of the matrix. The composition was to simulate a representative quantity of waste generation at a normal household [Finstein 1992; Aranda *et al.* 1999; Hogland and Marques 2000; Oorshot 2001; ROU 2002b]. Some free space was left for the worms to move to in case they found the initial condition (before the start of microbial action on the waste) of the newly added material unsuitable.

Nearly 800 grams of wet weight waste material was added to the box daily so as to achieve a stable composting rate. This was to ensure that the maximum amount of substrate, which was equal to half the weight of resident worms, was consistently maintained. If composting rate did not proceed as expected, the waste addition was to

be halved to 400 gm, but this did not happen in this test. The matrix was sprinkled daily with water to maintain adequate humidity. A section of the waste was tested to determine the amount of moisture required. Addition of water was required to make up the moisture level to the safe ranges of worms – approximately 80% w/w.

Temperature within the box was monitored regularly. A bimetallic thermometer was inserted half way into the mass to do this. The pH in the soluble extract of the food waste and the composting mass was determined using pH meter from Envirosensors 40603, by the Standard Methods [Clesceri 1999]. If the pH of the solids become too acidic or too alkaline for favourable vermicomposting, it was adjusted with appropriate waste food or with garden lime [ROU 2002a, 2002b]. This was done twice, on the 75^{th} day and 90^{th} day of composting as acidophilic pot-worms were seen to have proliferated indicating a low pH. Though this was not detrimental to the composting worms, it was decided to remove these organisms that compete for nutrients with other composting organisms and improve the pH through the addition of $50gm/m^2$ of garden lime.

High nutrient loading was tested in this experiment by applying fresh cow manure and duck droppings to the top of the composting matrix, procured from grazing lands nearby. These materials have very high nitrogen content (thus low C: N ratio) though lower pathogen counts unlike blackwater [Hansen *et al.* 1992; Haddon 1993; Aranda *et al.* 1999]. Tests were not undertaken of the effect of this high nutrient loading, as the objective of the experiment was to note only the system responses and to have a sustainable worm population under high nutrient loading conditions. It was decided to finish the tests when the box was full

7.3.2 Results, Inferences and Discussion

The food intake capacity of composting worms, as cited in literature, was seen to be dependant on many conditions such as the materials added, the moisture content, external weather patterns. In these experiments, a mix of different breeds of composting worms were seen to be in harmony with each other though slower in the substrate conversion rate. Worms are not reported to favour meat and fatty food, but in the long run, these materials also are taken up. As mentioned elsewhere, vermicomposting involves microbial composting, as worms consume the bacteria and protozoa along with degraded materials. Meat, cheese and fish particles were converted, though preference was for materials of plant origin, such as vegetables and coconut fibre.

One of the primary objectives of the project, to test the reported worm-loading rate of 10-16kg/m^2, was confirmed and obviously dependent on adequate waste material flow to sustain the population and their nutrient requirements. Such a high loading of worm biomass would be necessary for co-composting of biodegradable wastes and blackwater, as the amount of nutrients and moisture would be very high. Higher moisture rates need higher aeration in the substrate to avoid anaerobic conditions and a larger number of worms burrowing through the matrix could achieve this by creating adequate channels for airflow through the same. In addition, design of the system should incorporate forced aeration throughout the matrix.

The vermicomposting tests were undertaken with no soil or sand added to the mass, and data from literature that suggest composting worms behave different to

earthworms in their dependence to soil were affirmed [Dominguez *et al.* 1997; TNRCC 2001]. Being epigeic (litter dwelling), composting worms do not require soil to survive unlike earthworms that are anecic or (burrowing, soil dwelling) and endogeic (deep soil).

7.3.2.1 Effect of temperature

Wide variations in the ambient temperature slightly affect the processing temperature, though self-correction was observed. Only the moisture content of the added substrate and the composting matrix seriously affected the temperature inside the matrix. Fig 7.1 shows the ambient temperature and process temperature for phase 2 vermiculture tests. Though the ambient temperature varied widely, the process temperature (checked around mid day to accommodate thermal inertia) stayed consistent between 15-25^{o}C during the 4-month period that ranged between winter, spring and summer seasons. During this entire period, the process temperature never rose to higher ranges, unlike microbial composting where temperature usually rise as part of the mesophilic-thermophilic-mesophilic cycle.

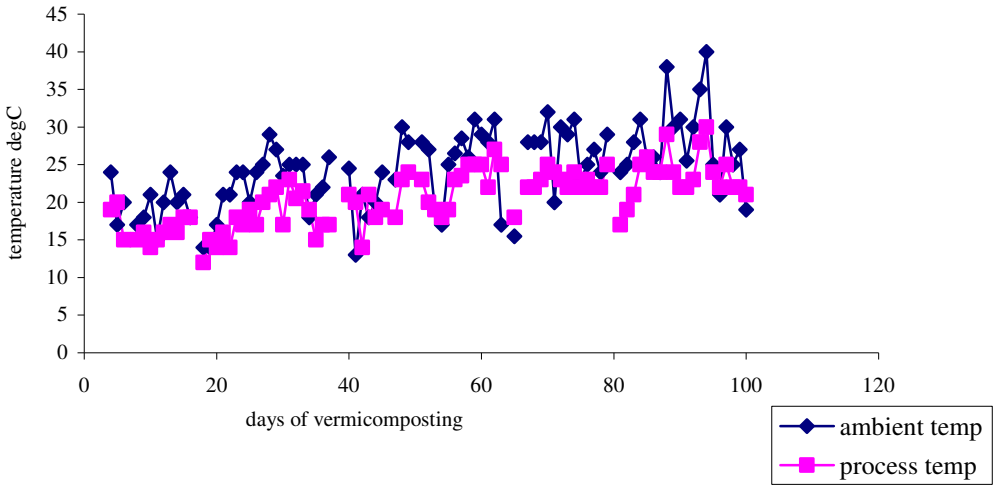

Figure 7.1 Variation in temperature in the vermiculture mass

It was observed that an increase in the ambient temperature initially caused a temperature rise in the matrix, but the increased evaporation caused heat removal leading to stable process temperature. Even with passive aeration, vermicomposting of putrescible wastes maintained aerobic conditions and temperatures favourable to the worm population by moisture removal through the channels created by worm burrowing. Moreover, due to the continuous movement of the worms and other creatures that took part in the process, the solids did not settle down thus leaving adequate interstitial spaces. In this regard, it could be said that artificial forced aeration was not a necessity in vermicomposting, under normal conditions.

7.3.2.2 Effect of pH

As mentioned before, pH is an important parameter in vermicomposting though worms can accommodate a range of pH from 5 to 9 [Edwards 1988]. Bacteria prefer a neutral pH and fungi prefer acidic pH [de Bertoldi *et al.* 1983] and these two groups of microbes play a leading role in composting and vermicomposting. For the tests, pH measurement was done on liquid extractant of the raw material and the solids in the boxes. Low pH levels were noted during the process, perhaps due to chemical changes in the substrate, and this caused an increase in numbers of white acidophilic pot-worms. These small worms were not hostile to the success of the vermicomposting, as they also took part in the process, but competition for the available nutrients could slow down the process in the long run. Thus, it was decided to add 50 gm/m^2 garden lime on the 75^{th} day of tests and this gave immediate results in reducing the numbers of pot worms. Another method successfully tried to remove

pot worms involved placing acidic food materials (cheese, orange peels) on top of the substrate and removing it once the pot worms had gathered on it.

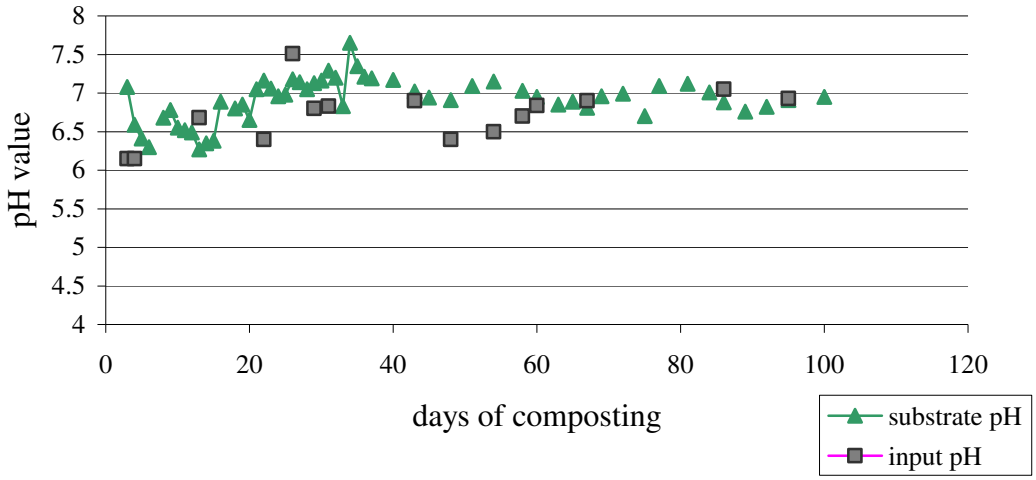

Figure 7.2 pH variation

The pH of the substrate matrix stayed in neutral ranges, with small changes following the pH of input material when supplied in considerable quantities (Fig 7.2). As reported in chapter 5, the self-correcting behaviour of vermicomposting could be a reason for the pH stability, the worm metabolic enzymes contributing towards this effect. This observation could be of value in designing and operating a blackwater composting system as the pH of raw blackwater and putrescible waste can be quite unpredictable. The pH could also be affected by the release of CO_2 (acidic) or NH_3 (alkaline) as by-products of microbial respiration with waste materials high in nutrients. Denitrification processes release H^+ ions causing a drop in pH [Tortora *et al.* 1998].

7.3.2.3 Material conversion

The total mass of substrate (dry weight) added in the vermiculture tests (including the 3 kg bedding provided at the start) of phase 2 was 13 kg solids over the testing period of approximately 3.5 months (August 2002 – November 2002; incorporating days without addition) excluding the live weight of the worms. The total water added during the entire vermicomposting period was approximately 1050ml. The final dry weight of the material excluding the worms was seen to be approximately 8.5 kg, with a reduction of 35%. This weight-loss could be assumed to have lost in the volatile form, as CO_2, NH_3, water vapour etc, in addition to all the water that was sprayed. Volume of the solid matrix was reduced only slightly. As the ambient temperature was always warm to hot, moisture removal was always through evaporation leading to no leachate at all for collection.

The type of food material added and its moisture content affected the progressing of the worm-action in terms of the time taken for the worms to start consuming it. Worms usually devour a number of microbes that degrade the waste materials along with semi-degraded materials. The degradation of the material is then completed with the enzymes produced by the worms and the microbes promoted by these enzymes. To start this process, microbial action needs to have started on the material, which will depend on the moisture content of the material and the structure and particle size of the material. It was noted that pieces of sturdy materials such as wood remained in the substrate without much change, whereas other more putrescible material such as banana peels and cooked/uncooked vegetable parts degraded more quickly. Some materials such as well-moistened coconut fibre and smaller items such as rice were consumed faster while large pieces of bread and pasta were given lower

preference. This could be due to the nature of bread that allowed growth of fungi (drier conditions – some are toxic to worms) and acidic pH of pasta.

Contrary to many published and ad hoc reports on vermicomposting, the mixed breed of worms were seen not to be averse to meat and fish wastes that were supplied in semi-cooked and cooked conditions. Meat and fish wastes were added on the 26th day of the experiments with chicken wastes on the 33rd day. It was noted that worms attacked the animal (beef, ham) meat faster, compared to chicken waste. The main reason for this could be the way of cooking, certain ingredients of the chicken preparation would have been too acidic. Another reason would be the fat content in the particular preparation, which again worms dislike [Darwin 1945; Jamieson 2000; Fraser-Quick 2002]. Microbial attack on chicken was also slower compared to other meat, perhaps caused by fat content or the cooking ingredients that might have acted as preservatives against microbial growth. It was noted that as the chicken pieces dried in the composting box, fungi started to grow which later disappeared.

Degradation of paper shreds and garden organics was effected by the presence of other more humid waste materials such as kitchen waste and manure. Towards the end of the process, only tiny pieces of the long paper shreds remained and the dry leaves had all been converted into vermicastings. Small sticks and wooden pieces still remained, which had higher lignin content and thus were too strong for the microbial community and worms to act on them [Stentiford 1992]. De Bertoldi (1983) had reported that the microbe *basidiomycetes*, which primarily degrades lignin, prefers completely static systems that are not practical in vermicomposting

due to the continuous movement of the active worm population which created a mini-scale ‘turning’ effect.

Addition of cow manure and duck droppings contributed to the performance of the worms, perhaps due to the higher organic nitrogen content and digested/degraded materials usually contained therein. These materials could have also increased the microbial content in the matrix. Addition of materials richer in nitrogen was the preferred method of improving the C: N ratio. For the purposes of this experiment, exact measurement of C: N was not considered necessary. However, it could be assumed that the dry garden organics added to the compost contained a very high amount of carbon that accommodated the addition of the N-rich materials. The composting process improved with the addition of dry garden waste, through increased worm-action in the substrate.

Waste materials were added to the substrate in different patterns, such as in long strips or at corners or at different spots. This was done to check the response of the worms to different food materials (different pH, composition and structure). In general, the worms were seen to migrate away from the new material at first, only to return later and start the consumption. This might be due to the fact that worms cannot chew or consume any waste materials directly; or they need microbial action to start degrading the material. Once microbial action appeared the worms almost always returned to the newly added material. This was observed for all the materials except when coconut fibre was added at first on the bedding material. The worms appeared to be immediately attracted to the coconut fibre.

If the freshly added material lacked adequate moisture content fungi started to grow, which repelled the worms. This was reversed once water was sprayed over the material or moist materials were added. Certain fungi could be toxic to the composting worms, but other fungal predators such as nematodes would flourish once the numbers of fungal species increase and these are also part of the composting cycle [Ingham *et al.* 1986*a;* Ingham *et al.* 1986*b*].

Appearance of the Indian blue worms in the worm community at the surface of the matrix was taken to indicate that food materials deep below the surface had been finished, due to the deep-burrowing nature of the creatures. Only the thin tiger worms were seen to wander off from the substrate in humid weather. This indicated that different worm species have different preferences and behavioural patterns, and this could be of use in successful operation of larger vermicomposting systems. Red wigglers were seen to grow in size more than all other species though red tigers were more prolific.

At the end of the vermiculture tests, the final product was separated into live worms and vermicastings. It was noted that the total waste materials including the initial bedding material had reduced from approximately 13kg to almost 8.5 kg, a reduction of 35%. This reduction, as discussed earlier, could have been lost as volatile substances or converted into worm biomass. The biomass of worms was seen to slightly increase from the initially added 1.6 kg to a final 1.8 kg, though ideally this should have been more. The reported doubling of worm population in 2-3 months [Bogdanov 2001] is practically unattainable under normal composting conditions

[ROU 2002a], unless this forms the objective of the experiment. Nonetheless, the small increase of 12.5% was encouraging.

7.4 Microbial composting

The purpose of a separate small-scale microbial composting experiment was to produce the degraded material that would be required for any later blackwater-composting project as a starting material. This experiment was also used to study the effect of temperature and moisture content on small-scale container composting without worms. Microbial composting is more widely practised for waste management and fertiliser production, but this is always at a larger scale and not at a scale envisaged for the intended experiments. This test was designed give to insight into the applicability of microbial composting in blackwater composting incorporated into the vermicomposting process.

7.4.1 Materials and Methods

The microbial composting mass was started with 2.5 kg dry garden organics comprising primarily of leaves and grass (C: N ratio 41), 1 kg cow manure (C: N ratio 18) and 1.5 kg of food waste (C: N ratio 16) to achieve a proportion of 50:20:30 and effective C: N of 29 [Haug 1993] with 1L water added for 40% moisture content, tested by drying a representative sample in an oven. This C: N calculation [SRSWS 1996] is formulated as:

$$\text{Effective C:N} = \frac{\left(\text{weight}^1 * \text{C:N}^1 + \text{weight}^2 * \text{C:N}^2 + \text{weight}^3 * \text{C:N}^3\right)}{\text{total weight}} \qquad \ldots 7.1$$

where weight[1] is the weight of material 1 and C: N[1] is the C: N ratio of the material 1.

$$\text{Therefore, Effective C: N} = \frac{2.5*41+1*18+1.5*16}{5} = 28.9$$

Composting progresses rapidly with a C: N of 30-35 and moisture content above 40% [IFAS 2002]. This experiment started with lower limits of these parameters to ensure that any addition of materials could not reduce the values. The materials were mixed well and filled into a plastic container of suitable size. Only the temperature profile of this matrix was tested against ambient temperature over a period of 5 weeks (Fig 7.3). Water was added by spraying over the composting mass from time to time, as required, for retaining the 30% moisture content. Moisture requirements were assessed from measurements of the moisture content of small samples. Aeration was another parameter used to control the performance of the microbial composting. Forced aeration was provided using a commercial fish-tank aerator at the rate of 30L/min.

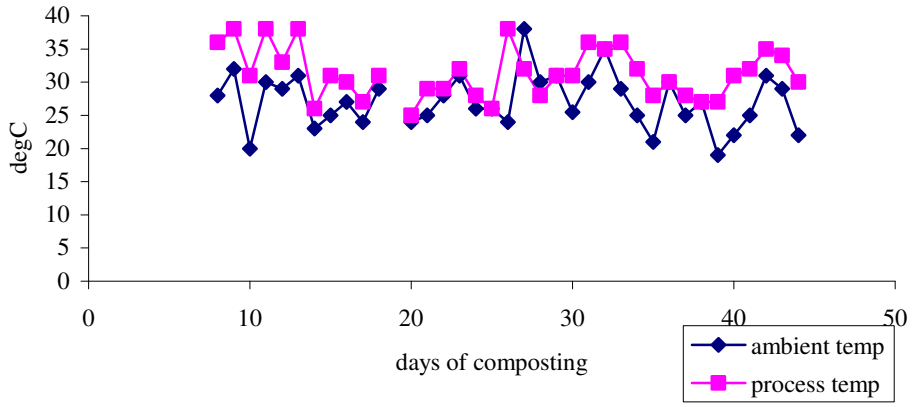

Figure 7.3 Temperature profile in the microbial composting mass

As noted in Fig 7.3, during the first 2 weeks of composting, the temperature profile was stable with the process temperature increasing. In comparison to vermicomposting, the ambient temperature had less effect on the process temperature, which was determined more by the moisture content and aeration, as well as the microbial activity, which in turn was determined by the materials available. Adding new materials always caused an increase in the temperature. On the other hand, reduced ambient temperature caused heat loss from the composting mass. After 2 weeks of processing, the box was covered with insulating materials to reduce this heat loss, though it did not give adequate protection.

It was speculated that the heat loss was causing moisture loss, leading to reduced microbial activity. To overcome this, it was decided to humidify the air that entered the composting mass. This was achieved (by the end of the 3rd week of processing) by passing the air through a column of water before entering the matrix. This helped reduce the moisture loss to an extent and thus the temperatures reached higher than earlier levels. But again the performance was not satisfactory due to slow rate of decomposition and high water addition requirements.

The microbial composting experiment was conducted for only 5 weeks, and the material was left to cure after this time frame. No more tests were conducted on this material other than occasional monitoring for anaerobic conditions. It was noted that the material continued to degrade further at a very slow rate in the absence of proper humidity.

The experiment showed that addition of moisture to a composting matrix improves the performance in both forms of composting. But compared with vermicomposting, microbial composting performed poorly. For a small-scale composting system, microbial composting has a higher risk of process failure while vermicomposting can achieve stable conditions and appears to be reliable once stabilised.

7.5 Conclusions

Moisture was found to be a very important parameter for worms, as it decides the internal temperature and biological activity, such as appearance of fungi. From the literature review presented in earlier chapters, the chemistry of vermicomposting is very much alike that of microbial composting and changes in pH and nutrients can affect the system. Composting is a natural process and therefore it has a capacity to direct itself to the optimum performance under normal conditions.

Generally, the results of the second phase of vermiculture tests indicated that the higher loading rate of worms of different breeds could lead to successful vermicomposting with random mixed Municipal Solid Waste as substrate. The experiments confirmed reports on the self-correction of pH and self-maintenance of suitable temperature ranges. A self-sustaining composting-worm population was developed during this experiment that could be useful for later experiments.

CHAPTER 8 EXPERIMENTAL PROTOTYPE DESIGN AND SETUP

8.1 Introduction

This chapter describes the design of the prototype of the blackwater waste treatment system. Existing knowledge obtained from the literature and preliminary work reported in earlier chapters, provided the background to this innovative design. Data from operation of the prototype vermicomposting unit is the prelude to a full-scale unit that can be implemented in actual situations. The development of a full-scale system will require not only the results from the prototype whose design is described in the following sections but also approval from relevant health authorities and others for onsite treatment of blackwater and putrescible waste.

For this study, the prototype blackwater and biowaste vermicomposting unit is designed with the expected waste input of a single person. The results from the prototype can then be optimised as a scalable design for a single household, a small housing complex (apartments) and a small village at community level, where several such single households or housing complexes could treat the wastes onsite with the benefits shared.

This chapter has three sections: an introduction into the design fundamentals for a vermicomposting unit, the design process and the construction of the prototype and

the final optimisation of the system as well as an introduction to the preparation of the materials for the testing of the prototype.

8.2 Design Fundamentals

The important factors for the successful design of a working vermicomposting unit, in no particular order, are:

1. Method of substrate addition
2. Expected quantity of waste input
3. Worm stocking rate
4. Expected quality of waste input and treatment
5. Hydraulic retention time (HRT)
6. Solids retention time (SRT)
7. Material movement within the system
8. Final collection of compost and effluent
9. Material of construction
10. Aeration – input, transportation and ventilation
11. Monitoring of process parameters

The relevance of each of these closely interlinked parameters is discussed in the following sections, based on literature reviewed in the earlier chapters.

8.2.1 Method of substrate addition

Solid waste materials can be added to the vermicomposting unit in different ways although it has to be convenient for the user. Liquid waste can be added along with the solid wastes. The required hydraulic retention time will determine whether the solid and liquid waste streams can be introduced together. For a short HRT, the liquid wastes can be added directly onto the waste matrix inside, for a longer HRT it

can be stored in a container for slow release. Storage is less satisfactory as blackwater is pathogenic and storage can lead to reactions taking place that may degrade the operation of the aerobic system.

A low-cost vermicomposting unit will have vertical flow of substrate under gravity, which will avoid the need for expensive mechanisms such as pumps and grinders. New material is added on top of the substrate with worms, the liquid waste and the degraded materials flowing downward under gravity. A vertical vermicomposting unit requires less floor-space.

8.2.2 Quantity of waste input

The design of a working prototype will incorporate a realistic waste input and also allow for variability in the input, consistent with household behaviour. In the prototype the design is scaled down to the waste generation equivalent of a single person. Data on per-capita waste generation is readily available. Results from a single person unit are scalable for households with different number of people, apartment complexes, a small communities or commercial centres, if the waste quantity and quality are known. Smaller systems are easier to work with, as no earlier studies on a similar system are available to assist with the design.

Per capita quantities of garden waste, kitchen/food waste, blackwater and other domestic waste such as paper shreds were considered in the experimental design. The quantities of the waste materials were calculated from the available data, to be added to the system. Volume and particle size reduction of the waste were to be monitored. As part of a separate study, it was planned to use the vermicomposting unit in

conjunction with a prototype greywater treatment system, which is also a small scale experimental prototype. Both systems are designed in the prototype stage for single person waste production.

The average organic waste generation per person per day (chapter 2) is a minimum of 700 gm dry weight of solid waste from all sources. Excreta waste is estimated at 400 gm wet weight [Aalbers 1999; Bernache 2003], with the output of a normal toilet per flush at 6L. The volume of the flush may decrease as the results of on-going research on optimising the ultra-low dual-flush toilets continues, with the volume possibly reducing to less than 4L per full flush. Seasonal variations can affect the quantities of garden waste added to the organic waste component.

8.2.3 Quality of waste input and treatment

The organic waste mixture from a normal household will contain paper-shreds, garden waste and kitchen/food waste including highly decomposable components. For the tests undertaken in this project a mixture of the waste was simulated. Table 8.1 gives the typical dry densities of domestic organic waste, on an 'as discarded' (not compacted) basis, along with the fraction of the total waste stream. Addition of blackwater (liquid pig manure) to this mixture adds to the putrescible nature of the substrate for the vermicomposting unit. The advantage of wet vermicomposting over traditional composting is that faster degradation of wastes results in better treatment. The high BOD (ranging from 2000 to 15000 mg/l [DLG-NSW 1998]), COD, nutrient content and solids content will be significantly reduced with vermicomposting.

The vermicomposting system designed for this study incorporates combined waste addition, that is, solids and liquids are added at the same point. The solid mass filters out the suspended solids in the blackwater, and passes the filtrate down under gravity. The filtered solids become part of the solid matrix and are converted into vermicastings.

Table 8.1 Typical characterisation of domestic organic waste components

Material	***Density (dry) (kg/m^3)***	***Fraction %w/w***	***Moisture content %w/w***
Paper waste	90	10	5
Food/kitchen waste	230	25	60
Human waste	-	5	60
Garden waste	100-230	45	50
Misc. organics (including manure)	150	15	15

Source: compiled from [Norstedt *et al.* 1992; Sincero and Sincero 1996; Halestrap 2001]

8.2.4 Hydraulic retention time (HRT)

The extent of treatment received by the liquid waste depends in part on the duration the liquid has been in the system, the retention time. Worms can survive in a high humidity environment (chapters 5 and 7). The higher the HRT, the better the treatment. But, as the liquid waste is added regularly, a high HRT can cause a build-up of liquid waste that will block the inter-particle spaces in the composting mass thereby creating anaerobic conditions and foul odours; leading to process failure. Therefore keeping the correct HRT is crucial. The method of adding the liquid waste will depend on the design HRT, which in turn is somewhat dictated by the amount and nature of solid materials in the substrate and the solids retention time.

For multi-phase systems such as wet composting systems, HRT can be expressed as:

$$HRT = V / Q \quad \ldots 8.1$$

Where V is the total volume of the system and Q is volumetric flowrate of the material. V is a design parameter whereas Q is affected by the density, volume and structure of the substrate. To extend the HRT without making the system any larger, recycling through the already composted part of the solid material will be beneficial. If any material is recycled within the system, either as a combination of solid and liquid material or liquid material alone through a volume of the substrate V_1, the residence time becomes extended depending on the volumetric flowrate (q) of that recycled material:

$$HRT = (V / Q) + (V_1 / q) \quad \ldots 8.2$$

Blackwater passes slowly through the interstitial spaces of the vermicomposting medium. A high humidity will saturate the substrate mass, thus the passage of the liquid will be faster. Drier substrate will delay the HRT. This will not affect the decomposing process adversely, but the wastewater treatment may not meet the expected targets of effluent quality and quantity. Keeping a steady liquid flow, proper HRT and reducing moisture removal by aeration are critical in the successful operation of a vermicomposting system. It should be noted that there is a certain amount of substrate flow control in the system, which also monitors the right moisture level required for efficient processing.

8.2.5 Solids retention time (SRT)

The duration for which the solid matter remains in the vermicomposting unit is the solids retention time for the system. Unlike HRT, SRT does not involve recycled material (material recirculated to the system). Thus, "SRT is the mean residence time of the feed solids excluding recycle" [Haug 1993]. For complete degradation of waste, the waste material needs to remain in the processing system for a full composting cycle. That is, the time required for the worms to fully convert the material into vermicastings.

One full vermicomposting cycle is approximately 1.5 to 2 months (chapters 5 and 7). The system size should be large enough to contain material for 1.5 months, including the incoming material of that time frame. After this time, material can be removed from the collection end of the system, while addition of fresh feed is continued at the input end. The removed castings will have to be stored for a curing time to provide time for remaining organic conversion reactions to complete and for the material to stabilise. This time frame will not be part of the system SRT. Normally, curing time required is approximately 4-6 weeks [Haug 1993; AS4454 2003].

8.2.6 Material movement within the system

For a low-cost vermicomposting unit, the material transfer within the system will be under gravity. Both liquid and solid phase substrate can move downward in a vertical vermicomposting unit under gravity. Movement of the liquid phase over the shorter HRT will be easier compared to that of solids during the longer SRT due to compaction that can arrest the movement of solids. When fresh waste is added on top

of the substrate matrix, worms will move upwards, leaving the vermicastings at the bottom, which can be removed for curing at the end of the SRT.

To avoid cross-contamination between the fresh material and castings, separate chambers will be helpful within the unit for the two different types of material. The system can be designed so that casings can fall to the next chamber under gravity. As raw blackwater is added along with the fresh waste material, cross-contamination of the filtered effluent can also be avoided. This will also help to avoid cross-contamination of raw blackwater and treated effluent.

8.2.7 Worm stocking rate

The quantity of waste treated per unit time is directly related to the stocking rate. For the prototype the stocking rate was estimated from the vermicomposting tests presented in chapter 7 and literature [ROU 2002b], given at 10-12 kg/m^2. The worm biomass available in the unit is critical to the successful operation of the system, as a low worm-stocking rate will result in reduced aeration, slower processing rates and waste material build-up. With wet composting, slow processing can result in anaerobic conditions at the bottom of the unit, giving off foul odours, thereby jeopardizing the aerobic treatment. As mentioned in chapter 5, worms are able to regulate their population size depending on the substrate available. The initial live weight of worms added in both chambers is decided based on the volumes of each chamber. This will be done in the presentation of the design, in section 8.3 of this chapter.

8.2.8 Collection of compost and effluent

The final products of the vermicomposting system are vermicastings and treated effluent. This effluent will have characteristics comparable to greywater and thus will be treated further in the greywater treatment system. The design of the system will be such that, the liquid is collected separately from the solids through a perforated plate below the solids, so that removal of the liquid at the end of the HRT will not disrupt the solids contained therein. A pump for removing the effluent to the greywater system will be included in the design.

After the composting cycle of 1.5-2 months, the solid residue (vermicastings) will be manually removed from the system and stored for curing. The design of the prototype will incorporate access to remove the solids. Access to the worm castings will either be at the bottom part of the solids-retaining volume of the unit, or via a demountable wall of the unit. Worms will have moved upwards to the area where fresh matter is available, so the castings at the bottom should be free of organisms. The castings at the bottom will be moist due to the filtered water.

8.2.9 Material of construction of the prototype vermicomposting unit

The unit needs to be sturdy, resist corrosion, have a good appearance, be easy to construct, and should not affect the processes in any way. The prototype vertical vermicomposting unit should be self-supporting.

The substrates can vary in pH from alkaline to acidic, therefore the material from which the unit is made should be resistant to corrosion. Seasonal changes such as cold, hot or humid weather can generally affect the process of vermicomposting. The

unit should buffer such external variations in temperature and humidity. HDPE plastic (cheaper) and stainless steel (more expensive) were initially considered. Stainless steel was chosen for prototype construction due to the facilities at UWS being better equipped for metal-working.

8.2.10 Aeration - Input, transportation and ventilation

Control of airflow to avoid anaerobic condition is important in composting. The provision of adequate air supply is an important factor in the design of the vermicomposting system. For the working prototype, the aeration is estimated as small. An air pump of suitable capacity, such as commercially available small aquarium aerators is suitable. The air can be humidity-saturated prior to entering the vermicomposting matrix if the latter is dry, by passing the air through a humidifier.

Due to the high moisture levels in the wet composting unit, aeration to all parts of the mass will be necessary. This is because high humidity can prevent air passage in the inter-particle spaces. A suitable network of perforated pipes running through the matrix is required. Ventilation of the exhaust will be incorporated in the design with vent-pipes of suitable length.

8.2.11 Other design aspects of relevance

Provision of monitoring facilities for this experimental prototype is included in the design. These include inspection ports and probe-access ports for thermometers and access areas for sampling of solids and liquids. Access to clean the different chambers is required, as cross-contamination has to be avoided between different

composting cycles. Biological growth within the tubes and aeration pipes is likely due to the high humidity substrate. Besides, any solid parts within the liquid transferring pipes can cause blockage.

8.3 Design of the Working Prototype

Based on the discussion of the previous section, the identified design parameters are:

- Volume, size and shape of the prototype
- Sections of construction panels – ease of construction, access and cleaning
- Process organisms – commercial worm farm produce
- Waste input and water filtration
- Diameter of monitoring probe-access ports
- Solid residue removal and outlet ports for treated effluent
- Aeration

These design parameters will be discussed separately in the following. The design diagrams are included in Appendix I. The prototype unit was constructed by technical officers at the School of Engineering Workshop. A conceptual diagram of the same is provided in Fig 8.1. A more elaborate diagram is later given in Fig 8.2 (section 8.4).

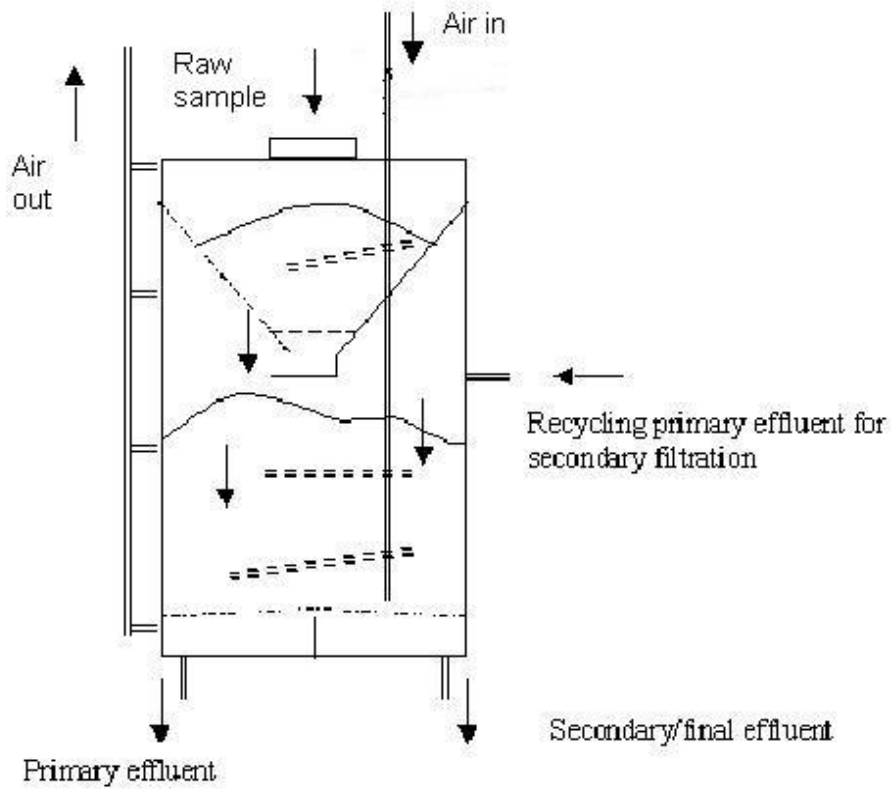

Figure 8.1 Conceptual diagram of the prototype – internal view

8.3.1 Volume, size and shape of the whole prototype

The quantity of raw solid waste is more important in deciding the volume and size of the unit. It can be estimated that the average biowaste production of a single person in the developing world is around 700 grams/day (approximately 5kg/week). Most composting worms consume waste between half up to their body weight per day (chapter 7).

To avoid system failure, no more biowaste can be added than what the stocked worms can process in a week. This would mean a minimum worm biomass of 5 kg. This worm population is divided into equal proportions for the two chambers – one receiving fresh waste and the other receiving partly degraded material from the first

chamber. Therefore, the design surface area would be that for 2.5 kg live worms. At the minimum 10 kg/m^2 worm stocking rate prescribed in literature this becomes 0.25 m^2 surface area for the vermicomposting unit. The designed waste load is given in Table 8.2.

Table 8.2 Different waste materials and volume calculation (based on Table 8.1)

Material	***Weight (kg) / week***	***Volume (m^3) / week***
Paper waste	0.50	0.006
Food/kitchen waste	1.25	0.006
Pig waste (solids)	0.25	0.001
Garden waste	2.25	0.01
Misc. organics	0.75	0.005
Total	**5.00**	**0.028**

The volume is based on the weight of the waste material and the density where available (Table 8.1). For example, for paper waste, the weight is calculated based on the weight of the total waste and the fraction,

Weight of paper component added: total weight of waste * percentage of paper stream = 5kg (total) * 10 % = 0.5 kg.

Volume of paper component added: weight of paper component / density of the material = 0.5kg / 90 kg/m^3 = 0.00556 m^3.

The volumes for other components of the waste stream are calculated accordingly. These data are used in calculating the total volume of the unit.

The total volume of waste added is approximately 0.03 m^3 per week. Per composting cycle of maximum 8 weeks, this requires 0.24 m^3 volume. The height of the unit required (assuming a square cross-section) will be 1m with the surface area of 0.25 m^2. In a practical composting cycle of 6 weeks, the volume required will be 0.18 m^3, leaving free space of 0.07 m^3 within the whole unit. The volume reduction achieved

in vermicomposting is not taken into account in the design calculations, though this will be considerable for the degraded materials. But the design should contain the non-degraded materials that larger volume chambers.

A square or rectangular cross-section for the unit makes the construction of the system simple. A square cross-section is chosen, with 0.5m sides, giving the required surface area of 0.25-m^2. The required thickness of the steel panels is at least 1.5mm for welding.

8.3.2 Sections and components of the prototype

The shape of the primary (waste-receiving) chamber (chamber 1) of the unit is V-shaped hopper with sides angled at 30 degrees (Appendix I Fig I.2). The maximum depth available in this hopper chamber is 350mm. This section of the unit will have SRT of 2 weeks by which time the worms within this chamber will have degraded the material to considerable extent, particularly in particle size reduction (based on observations during the preliminary tests presented in chapter 7). The volume of this section to hold waste for 2 weeks will be 0.06 m^3 (Table 8.2). One side of the V-hopper will be made of perforated (6mm diameter holes at 10mm spacing) steel plate that will allow filtration of liquid waste to the bottom chamber that has partly degraded waste material. This will allow further filtration and treatment (Appendix Fig I.3 and Fig I.4).

8.3.3 Addition of solid substrate

Food waste for the experiment was collected from the University cafeteria, while garden waste and paper shreds were procured on site. Additional organic materials, such as cow manure and coconut fibre were collected from the nearby dairy farm and market. Some mature castings from previous test run was added to each subsequent run. This was done to assist the worms in acclimatising to the environment within the unit.

Addition of fresh solid waste is through a chute at the top. This chute is 150mm in diameter and 50mm high (Fig I.8). The top panel of the unit, on which the chute is connected, is removable, for visual inspection of the top chamber. This will also allow spreading of the waste, if required.

8.3.4 Process organisms

A mix of different worm species was purchased from a commercial worm farm. The approximate mix of different worm species is as per Table 5.5 in chapter 5. A 12kg/m^2 worm stocking rate is applied. The top chamber (V-hopper) will have 3 kg of worms while the bottom chamber will have 9 kg worms. This stocking rate is chosen based on the volumes of the different chambers. The worms are shipped in mature vermicastings whose weight is equal to the worm-biomass, and this material will be used as the initial bedding material.

8.3.5 Addition, filtration and removal of wastewater within the system

Wastewater is added along with the solid waste matter at the top of the system (Fig II.1 and II.2). Partly decomposed solid material from the top chamber will fall to the chamber beneath under gravity, once particle-size reduced by actions of worms, through a breaker mesh panel of 20mm squares (Fig I.5). A thin layer of fibrous material (hay) prevents the initial bedding material from falling through the mesh. The structure of the chamber (chamber 2) that receives the partly degraded matter from the V-shaped chamber is such that the waste material on one side receives the primary-filtered wastewater (secondary filtration) and the other side receives the filtered effluent). A bottom plate with perforations is bent at the middle upwards with side slopes of 5 degrees to facilitate the flow of filtered wastewater (Fig I.6).

A peristaltic pump was initially considered to pass secondary filtered water to recycle, but it was later decided, based on the small volume of water and cost of pump, to recycle the water manually. A small water holding tank is provided under the composting chamber 2, partitioned to separately hold water from secondary filtration and tertiary filtration, without cross-contamination (Fig I.7). 20mm long stainless steel pipes are welded onto the bottom of the unit for removal of the liquid.

A submerged bilge pump removes the collected tertiary filtered water to the greywater tank (Photographs given in Appendix II). This pump could be run from solar power. This is situated in an external collection tank, fitted with a level switch, so that the pump will be switched on automatically when the treated water reaches a volume of 2 L and turned off when the water has been removed completely from the

external collection tank. Sampling of the final effluent from the prototype is undertaken from this external tank.

8.3.6 Access for monitoring

Access to the inside of the unit for measuring probes such as thermometers is through four access port constructed on the front wall of the unit with 15mm diameter holes. These holes are kept closed with black wiring tape when not in use to prevent worms escaping in humid weather and at night. Long-stem thermometers (250mm in length) that reach up to the middle of the composting mass are used.

8.3.7 Collection/removal of material and cleaning

Solid residue for curing, at the end of one complete composting cycle (SRT), is removed from the front section of the unit. The idea of a separate access door was discarded for ease of construction.

8.3.8 Aeration equipment

As the prototype is a closed unit, aeration is crucial in the successful operation of the unit. A fish-tank aerator pump sufficed for the purpose. The air is channelled through PVC conduits (Appendix Figs II. 8-11). A commercially available air pump of 200L head, 30L air/min at 0.02-0.03 MPa pressure was selected (Appendix Fig II.3). The pump could be run from solar power (power requirements in Table 8.4).

The air is passed through a humidifier (bubbled through a water-bath) so that it is saturated with moisture. This is done to avoid over-drying of the vermicomposting

matrix. Unlike microbial composting, vermicomposting can sustain higher humidity levels. The air is passed through a network of 12mm internal diameter PVC conduit pipes (Fig 8.2 and Figs II.8-11). The conduits are perforated for air passage, with 1.5mm holes (Fig I.2). This size will prevent worms from entering the pipes. The free ends of the pipes are fitted with PVC end-caps.

Four holes on one side of the unit are designed for connecting the pipes for venting the air (Figures in Appendix II). PVC conduits will be connected to these holes, which will lead the air to a vent-pipe. All PVC pipes are of 12mm internal diameter, 15mm outer diameter. The vent holes are located such that air from the water holding tank, above the solid matter in the lower and upper chambers is vented out, with an additional hole within the solid matrix in the lower chamber. The conduit on this latter hole has a perforated (1.5mm) end cap to prevent worms and solid matter from entering the pipe.

8.4 Summary of design dimensions and accessories of the vermicomposting prototype

This section summarises the design and provides the design details ‘at-a-glance’. The accessories fitted to the prototype are also presented in tabular form. The tables also provide the cost of construction of the unit, where available. The final set up is represented in Fig 8.2.

Table 8.3 Prototype dimensions

Whole Unit	Material	1.5mm stainless steel sheet
	Shape	Tower
	Cross section	Square
	Sides	0.5 m
	Height	1 m
	Volume	0.25 m^3
Primary chamber	Shape	V-hopper
	Sides	One side perforated 6mm holes, other side plain, both sides angled at 30^o
	Bottom panel	25 mm square mesh
	Maximum height	350 mm
	Volume	0.06 m^3
Secondary chamber	Ave. height	600 mm
	Resulting volume	0.15 m^3
	Bottom panel	6mm diameter perforated; inverted-V shape at 5 degree slope
Water holding tank	Height	100 mm
	Volume	0.025 m^3

Table 8.4 External fittings to the prototype unit

Equipment	***Description***		***Units***	***Unit price***
MAP30 electromagnetic aeration pump	200 L head, 30 L/min capacity, Pressure 200-300 mb (0.02 – 0.03 MPa), 240V AC, 10W		1 no.	$ 60-85
PVC pipe	Φ ID 12 mm	Φ OD 15 mm	4 m.	Available
PVC 'T' connector	Φ ID 15 mm	Φ OD 18 mm	3 nos.	Available
PVC 'L' connector	Φ ID 15 mm	Φ OD 18 mm	2 nos.	Available
PVC 'X' connector	Φ ID 15 mm	Φ OD 18 mm	1 no.	Available
PVC end caps	Φ ID 15 mm	Φ OD 18 mm	10 nos.	Available
Rule 360GPH Bilge pump	Small, 12V DC, 12W power, 22L/min capacity		1 no.	$ 120
Level switch	Erecta switch (Compac Engg Inc.)			$10 approx
12 V DC power supply for the bilge pump				Available
10 L bucket	As water holding external tank		1	Available
Thermometers long	Regal bimetallic rear-stem dial $^{-}10$- $^{+}110^o$ C		1 no. each	$ 100 approx.
	Red spirit long stem $^{-}10$- $^{+}110^o$ C			Available

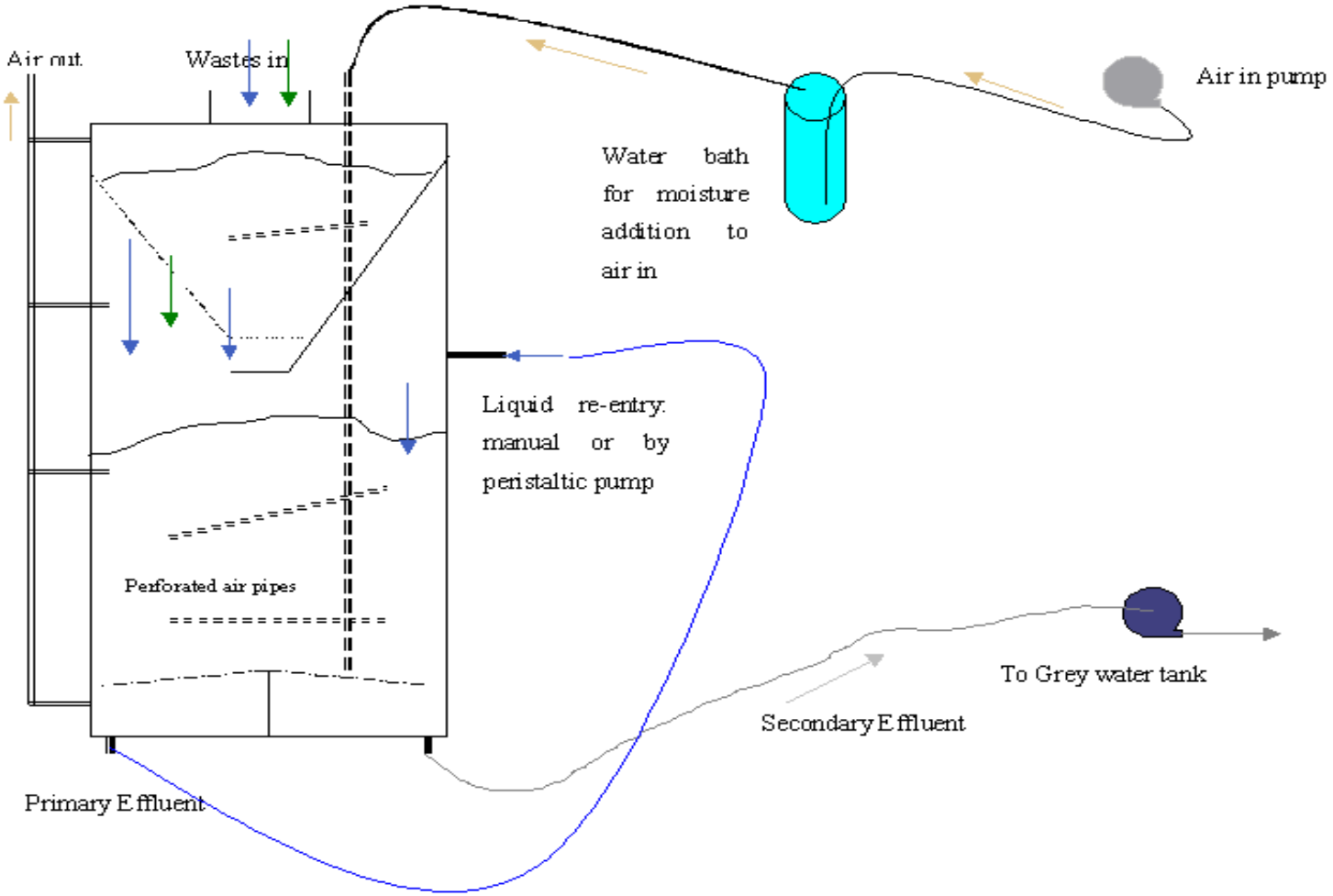

Figure 8.2 Conceptual design of the system

8.5 Conclusions

A vermicomposting prototype unit is designed for testing the hypothesis based on waste generation data for a single person. This chapter described the design parameters and other factors of relevance. The design was presented with the measurements and drawings are included in Appendix I. Details of the different sections and material flow were described in relation to the design of the overall system. The waste substrate preparation was also mentioned. The design is scalable to the waste generation of a household, a small housing complex or at a community level. The prototype will be tested for different composting cycles and the data of the same will be presented in the following chapters.

CHAPTER 9 WASTEWATER TREATMENT IN THE VERMICOMPOSTING PROTOTYPE

9.1 Introduction

The main objective of the vermicomposting system reported in this thesis is to treat blackwater to a level where it can be considered comparable to greywater for further treatment and to reduce putrescible waste to compost. This chapter focuses on wastewater treatment and presents the details of the research method, including the preparation of "standard" waste materials for the test, and the methodology of the experiment. Some details are also presented on the nature of the transformations in the liquid waste as it is treated in the vermicomposting unit. Discussion of the solid waste treatment experiments is presented in the next chapter.

During the vermicomposting process the liquid waste undergoes many changes, with notable reductions in many parameters including TSS, pH, conductivity, DO, BOD, COD, ammonia and pathogen content. Some other parameters – TDS and nutrients (N & P) – also vary considerably. The method of analysing and describing the processes in the vermicomposting system can be complex and very time consuming. The approach adopted in this thesis relates to a simple input-output model, with less attention paid to the dynamics and processes within the treatment system. The advantage of this approach is that it reduced the complexity of the analyses and brought the project within an achievable timeline. Those parameters that are examined relate to the modelling approach described above. A drawback of this approach is that

further work is required to validate the theoretical understanding obtained. More detailed analysis of the dynamics of the system will be the matter for future research.

9.2 Materials, Sampling and Test Methods

The design of the vermicomposting unit has already been presented in chapter 8. Tests were conducted over a period of 11 months (December 2002 – November 2003) and encompassed all the 4 seasons so that effects of weather patterns could be observed. This time frame covered seven trial runs, each equivalent to one composting cycle (SRT) of approximately 1.5 months (Table 9.1). The transformation in the liquid waste and changes in outputs was measured by comparing the respective parameters in the raw blackwater (liquid pig manure) and the final effluent. The effluent was also sampled and tested after the primary filtration (the first stage of treatment in the system). While the interest was in the input and outputs from the system, it was thought that an occasional examination of the treatment train at the end of the primary treatment stage was warranted and could assist in assessing the design of this important part of the total system. The analysis was also considered useful in the assessment of the level of risk in handling the liquid as it was transferred to the recycle point (ref: Fig 8.2).

Table 9.1 Duration of different trial runs of vermicomposting prototype

Trial number	***From***	***To***
1	5-Dec-2002	30-Jan-2003
2	1-Feb-2003	20-Mar-2003
3	21-Mar-2003	5-May-2003
4	6-May-2003	23-Jun-2003
5	24-Jun-2003	5-Sept-2003
6	6-Sept-2003	15-Oct-2003
7	16-Oct-2003	17-Nov-2003

This chapter first discusses the material preparation for the operation of the prototype, the parameters of interest, sampling protocol and the test methods. The results and detailed discussions on the transformations in the liquid pig manure, as applied in the vermicomposting prototype tests, are then presented.

9.2.1 Preparation and addition of materials for vermicomposting

The solid substrate used to filter the blackwater was added to the treatment system as prepared using the ratios given in Table 8.2. The mass of solid waste to be added to the system was weighed on a kitchen scale. Use of un-sophisticated weighing equipment was tested against a measuring scale accurate to grams and was found to be satisfactory. These were mixed by hand and applied on top of the existing material in the upper chamber in the unit. Initially, in each composting cycle, the only material in the chamber was the bedding material containing the worms. The lower chamber contained partly treated solids, initially from the earlier vermiculture tests and subsequently from earlier composting cycles to provide suitable habitat for the worms. At the end of each composting cycle (each treatment trial), the worms were harvested by hand for re-addition to the system. Baby worms were harvested from the material at curing stage after a time period of 2 weeks and added back to the system.

The liquid pig manure (blackwater) was stored in an overhead container of volume 25-L connected to the inlet of the upper chamber (V-hopper) of the prototype via a clear plastic tube (Photographs given in Appendix II). A valve at the bottom of the container controlled the flow of liquid. The liquid was manually stirred prior to application to the unit in order to simulate the turbulence caused by flushing of the toilet and to homogenise the wastewater. A volumetric scale on the side of the container gave the amount of liquid added. The addition took place in the morning hours. Four litres of raw pig manure was added daily, representing the output of an Ultra Low Flush toilet. Usage of such low-water-usage installations at houses could add value to the residential waste management system, when applied in real world. Changes in the effluent on long-term containment could be the subject of future studies.

9.2.2 Assessment of system performance

In order to assess the system performance in terms of its applicability in the real world, the main parameters of interest focused on the pathogen reduction, nutrient conversion and pollutant removal. These were selected based on the human and environmental health considerations for blackwater treatment. The choice of parameters was also based on the available test equipments for routine testing. The main parameters of interest in this study are the pathogenic content (as faecal coliform count), suspended solids and turbidity, BOD, DO, conductivity, pH, ammonia, nitrate and phosphate.

Reduction in faecal coliform and indicator E.*coli* as CFU/100ml (colony forming units) were tested. The bacterial content of the liquid waste poses a biohazard, which needs to be reduced, and the vermicomposting method is envisaged as a low-cost treatment option for this. Suspended solids contribute towards high turbidity and BOD, which contributes to the potential anaerobic tendency of blackwater. As blackwater/liquid pig manure has undergone anaerobic reactions, it has very low Dissolved Oxygen content. This, if left untreated, can impact on the natural environment upon release and therefore testing for DO is important. COD values have been used in designing biological waste management systems, and is useful in predicting the bacterial population growth [Münch and Pollard 1997]. Blackwater contains urine and generates high amount of ammonia, which is toxic. Measuring the conversion of N from ammonia to nitrate form is important.

9.2.3 Sampling protocol

Samples were taken at the entry point, as the raw blackwater was added to the upper chamber; and at the final exit, where the liquid was temporarily collected in the external tank prior to pumping to the greywater tank. These two sampling points enable an input-output model of the liquid wastes to be developed. Samples were collected in clean plastic containers, in the required volumes as per the test protocols. The collection and handling of samples is mentioned in Table 1060:I of the manual Standard Methods for Examination of Water and Wastewater [APHA 1999], the relevant parts of which are reproduced in Appendix VI of this thesis, and the guidelines from the manufacturers of the specific instruments used.

Sampling of the raw wastewater and the final effluent was undertaken on the same day as the blackwater was applied. Initially this was at done twice weekly (Mondays and Thursdays) as it was decided that until more information became available from this sampling pattern it was not possible to determine whether the sampling frequency was sufficient, or whether the system was over or under sampled for the purpose of modelling its performance. It transpired that the sampling frequency appeared satisfactory, but for the sake of confirmation, from the eighth month (August 2003) sampling was undertaken on a daily basis. Results from the initial period of 8 months gave indication that the process was progressing well. Weekends were not included in sampling.

Not all parameters were analysed during the early composting cycles due to cost considerations and equipment availability. Regular analysis for some parameters (pH, conductivity, TSS, TDS and turbidity) started with the first batch, and ammonia, nitrate, phosphate, DO, BOD and COD were analysed only at weekly intervals. The effluent derived from the primary filtration part of the treatment system was included in the analysis from May 2003, in order to assess the treatment obtained during the initial stages of liquid transfer in the system. Regular sampling for microbiological analysis started on raw wastewater and the final effluent from the 7^{th} batch (Table 9.1). Organic shock-loads (spike tests) were applied in the form of twice the volume of normal addition of blackwater during all trials except the first one.

The volume of raw blackwater taken for analysis was approximately 150ml; this was sufficient for testing. More sample volume was required of the effluent from the system than of the raw influent because of the low BOD of the effluent. Hence, the

volume of final effluent taken for sampling was approximately 750ml, which was sufficient for all the parameters to be tested. Occasionally the effluent after primary filtration was collected in 600ml volume, sufficient for testing all the parameters. The samples were taken to the laboratory; samples for microbiological analysis were refrigerated at $4^{o}C$ while samples for nutrient analysis were frozen, unless analysed the same day.

9.2.4 Test methods, quality control and quality assurance

All parameters were tested in duplication with blanks. Instruments were calibrated against standard samples [APHA 1999] for quality control (Table 9.2). Duplicates were measured using different instruments for intra-laboratory comparison on a monthly basis. Manufacturer's guidelines on the operation of the instrument were followed. The test methods and instruments are given in detail in Appendix III. Random samples were sent to a commercial laboratory for testing the physical and chemical parameters for inter-laboratory quality assurance. All microbiological tests were carried out at the NATA accredited Australian Government Analytical Laboratory (AGAL) and it followed its own procedures for QA/QC.

The choice of test methods for the chemical parameters was partly based on available instruments and reagents that would allow high range measurements, as the samples were expected to contain very high amounts of nitrogen and phosphorous. The test methods for the instruments conformed to the relevant standard APHA method and gave the same results. Colorimetric methods were used as the spectrophotometers were easier to use with the high number of parameters to be analysed on a regular basis. HACH 2400® and HACH 2000® spectrophotometers were employed in the

regular testing of the parameters and validated against standard methods. These were pre-calibrated and did not warrant regular calibration, as per the information in the equipment brochure.

Specific electrode probes dipped in thoroughly homogenized sample were used for pH, conductivity, TDS and temperature measurement. These and other instruments were regularly calibrated against standard solutions (Appendix III). TDS measurement followed standard methods. Conductivity readings were further validated with a calibrated Hydrolab field instrument.

Sub-samples were taken from the homogenised sample for analysis of other parameters and refrigerated for microbiological analysis. Duplicates were run for all parameters and blank tests were conducted as per the tests methods for each parameter. For DO, COD and BOD_5, the instruments were standardised against tap water and deionized water. All measurement procedures conformed to Standard methods for the examination of water and wastewater [APHA 1999].

Dilutions of the order of 500 to 1000 were necessary for testing for COD, ammonia, nitrate and orthophosphate (reactive P) as the concentrations were high. At times, dilution to the order of 1 in 2 or 3 was necessary for turbidity, as fresh raw samples contained high amounts of particulate matter (more than the 4500 NTU that could be directly measured by the available instrumentation). Guidelines from the manufacturer of the instrument were followed in these cases for accuracy and precision. The instruments Oxidirect® and Oxitop®, used for BOD_5, allowed analysis of undiluted samples for high BOD_5 samples. Table 9.2 summarises the tests and

instruments used and Appendices III and IV provides detailed methodologies and photographs of the instruments used.

Table 9.2 Test methods employed in analysing the identified parameters

Parameter	**Instruments and test method**		**Standard methods [APHA 1995]**
pH	Metrohm 713 pH meter Envirosensors Multiline pH meter		Method 4500-H^+ pH value
Conductivity	YSI 3200 Conductivity meter HACH CO150 conductivity meter		Method 2510 B – laboratory method
	Datasonde4*a*® Hydrolab		
TDS	Method 2540 C Total Dissolved Solids dried at 180°C (Thermoline™ oven)		
Turbidity	HACH 2100N turbidimeter		Nephelometric method 2130 B
TSS	Method 2540 D Total Suspended Solids dried at 103-105°C		
DO	YSI85 DO meter YSI DO200 DO meter		Membrane electrode method 4500-O G
	Datasonde4*a*® Hydrolab		
BOD_5	Oxitop® manometric system (WTW Instruments); Thermoline™ incubator		5-day BOD test method 5210 B
	Oxidirect® respirometric system (by Lovibond) with Lovibond™ incubator		
COD	HACH2400	Reactor digestion method 8000	Closed reflux colorimetric method 5220 D
	HACH2000		
NH_4-N	HACH2400 HR salicylate 10031		Phenate Method 4500-NH_3 F
	HACH2000 Nessler method 8038		
	Datasonde4*a*® Hydrolab NH_3 probe		
NO_3-N	HACH2400	Cadmium reduction method 8039	Cadmium reduction method 4500-NO_3^-
	HACH2000		
PO_4-P	HACH2400	Molybdovanadate method 8114	Vanadomolybdophosphoric acid colorimetric method 4500-P C
	HACH2000		
Faecal coliform & e.coli	Membrane filtration with medium: ColiID (AGAL)		Membrane filter technique – method 9222

9.3 Results and Discussion of the Reduction in the Physical Parameters Between the Influent and the Effluent

This section presents the results of monitoring for total suspended solids (TSS), turbidity, total dissolved solids (TDS) and conductivity (physical parameters). Transformations are separately analysed for each composting cycle. This is done because at the end of the SRT the solids are changed and the system is disturbed, and the whole process is repeated in the next composting cycle. The results are represented here as percentage variations (percentage difference between influent and effluent values upon influent value) rather than actual individual parameter readings to facilitate direct evaluation of the system performance and also due to the widely varying values for the input parameters.

Table 9.3 Variation in physical parameters between influent and effluent

Trial #	***Data from Excel spreadsheet***	***TSS (Reduction)***	***Turbidity (Reduction)***	***TDS (Increase)***	***Conductivity (Increase)***
1	% Variation	89.92	72.39	53.95	60.92
n=15	*Std Dev*	*7.11*	*19.19*	*45.89*	*30.59*
2	% Variation	78.13	87.84	104.22	89.97
n=13	*Std Dev*	*9.27*	*7.33*	*64.22*	*58.94*
3	% Variation	93.02	90.8	90.62	78.88
n=12	*Std Dev*	*3.09*	*8*	*19.39*	*20.32*
4	% Variation	94.98	93.4	55.37	48.86
n=14	*Std Dev*	*2.35*	*6.51*	*22.8*	*20.02*
5	% Variation	87.23	84.5	80.84	81.65
n=11	*Std Dev*	*11.34*	*23.43*	*47.5*	*44.73*
6	% Variation	96.52	96.51	37.9	34.32
n=22	*Std Dev*	*2.1*	*1.16*	*30.02*	*23.26*
7	% Variation	88.67	94.3	127.45	119.0
n=14	*Std Dev*	*5.6*	*3.73*	*38.38*	*26.55*

(n = number of samples in each trial run)

9.3.1 Total Suspended Solids

An overall mean reduction of 89.32% in TSS between influent and effluent from the seven trials during the entire testing period of 11 months was observed (Table 9.2). The raw blackwater contained a mean 4030 mg/l TSS while that of the final effluent was 278 mg/l. The minimum reduction (55.12%) was observed during trial 5 (low influent TSS, average effluent TSS). The highest reduction (99.05%) achieved was during trial 6. No particular trend could be observed from the reduction readings, either within trials or between them (Fig. 9.1).

The intermediate reduction in TSS, that between raw wastewater and the primary effluent, and that between the primary effluent and the final effluent varied widely, perhaps because of the quantity and compaction in the solid matrix. An average reduction of 74.24% was observed between the blackwater and the primary effluent, while an overall reduction of 64.26% was achieved between primary and final effluents. Analysis of primary effluent for most parameters started only during the fourth trial (sample 118 in May 2003 – 6^{th} month of overall monitoring).

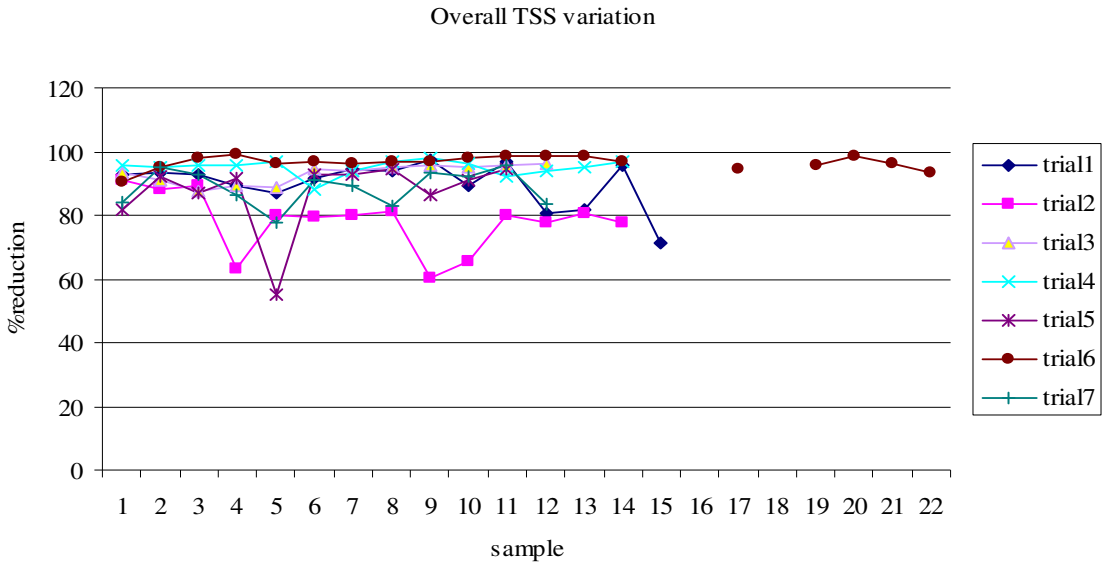

Figure 9.1 Overall TSS reduction between blackwater and effluent in all 7 trials

The removal of suspended solids during the filtration through the vermicomposting matrix ranged between 80 and 99%. The solids trapped in the matrix became part of the solid mass, which then underwent considerable transformation by the action of worms and microbes. Fig 9.2 shows the mean TSS reductions over the different trials (given in Table 9.3). Each trial produced results similar to the others in terms of reduction in TSS.

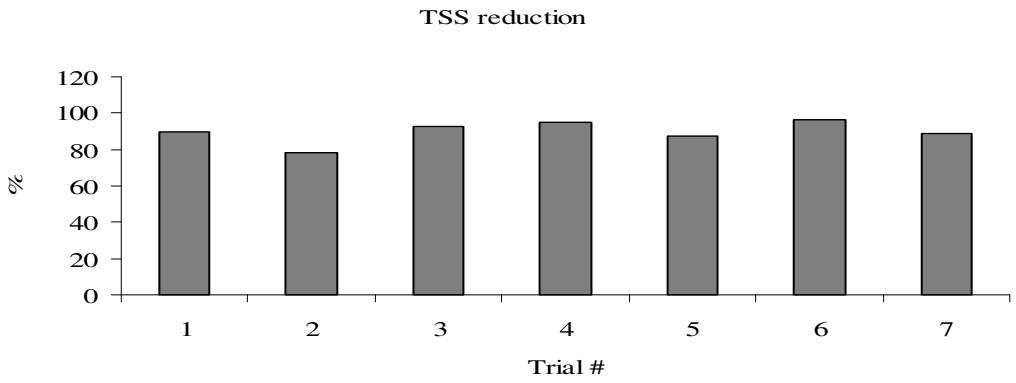

Figure 9.2 Mean TSS reductions over the entire operation of 7 trials

9.3.2 Turbidity

Turbitidy is correlated with TSS, although sometimes poorly, so the trends in turbidity were expected to be similar to those in TSS. The turbidity reductions and trial means are given in Figs 9.3 and 9.4. Trials means are also given in Table 9.3.

An average reduction of 88.77% was observed across the entire treatment period. The highest turbidity reduction was observed during trial 6, of 98.33%; while the minimum was during trial 5, of less than 15%. A reduction of more than 75% was reported for approximately 92% of the whole sample population. Generally, the final turbidity of effluent remained between 50 and 250 NTU except for the initial trial, where it was above 300 NTU. Later trials of the vermicomposting treatment achieved greater turbidity reductions, so that the final effluent could be compared to greywater. The removal of solids and fine suspended particles in blackwater has contributed towards the reduction in turbidity.

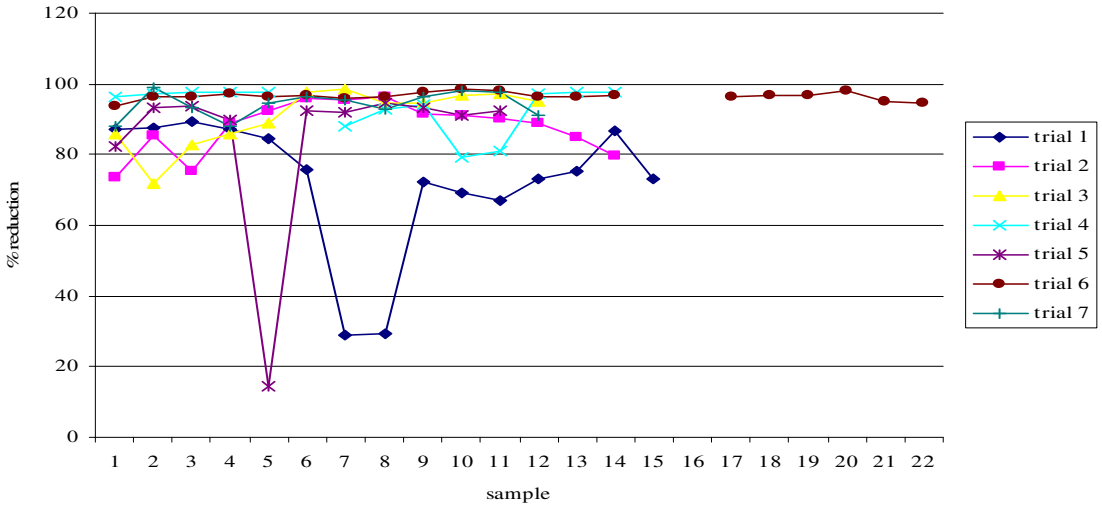

Figure 9.3 Overall reductions in turbidity in all 7 trials

Within each trial, the reduction of turbidity somewhat improved towards the end of the composting cycle, though this was proportional to the turbidity in the raw wastewater. The increased solid volume in the composting matrix contributed towards filtering the solids and turbidity-causing matter. The results are similar between each trial.

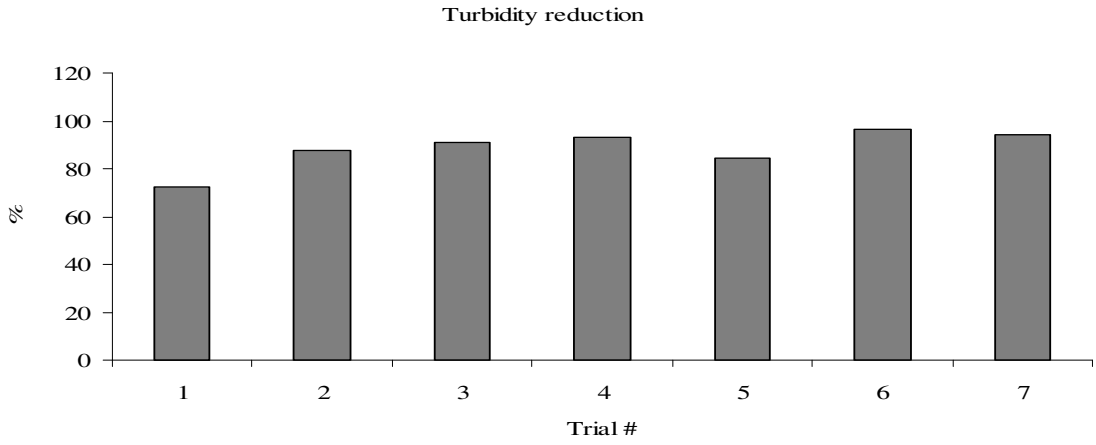

Figure 9.4 Overall mean turbidity reductions

An average turbidity reduction of 67.4% was observed between raw blackwater and the primary effluent, preceding a reduction of 71.08% between primary effluent and the final effluent.

9.3.3 Total Dissolved Solids

Most TDS readings increased between the raw blackwater and the treated effluent at an average 74.77% over the entire testing period of 11 months. The highest increase was for over 202% for sample 160 during trial 7 and the highest reduction was for 22.45% for sample 149 during trial 6. The readings fluctuated widely and gave no particular trend, perhaps due to varying content of nutrients in the raw wastewater and changes in temparature and evaporation rates. Fig 9.5 gives the variation of TDS over the entire experiment period and Fig 9.6 gives mean variations for the different trials (Table 9.3).

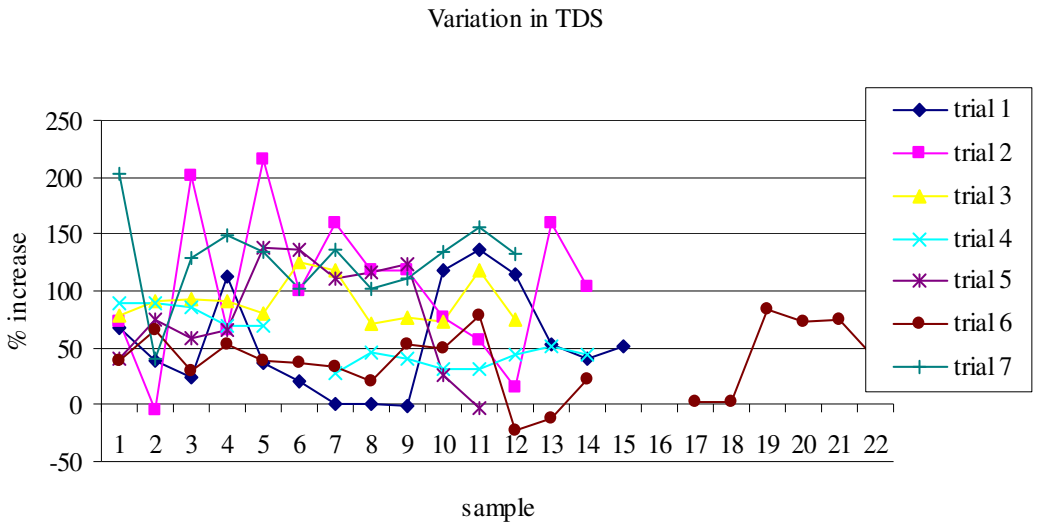

Figure 9.5 Overall variations of TDS

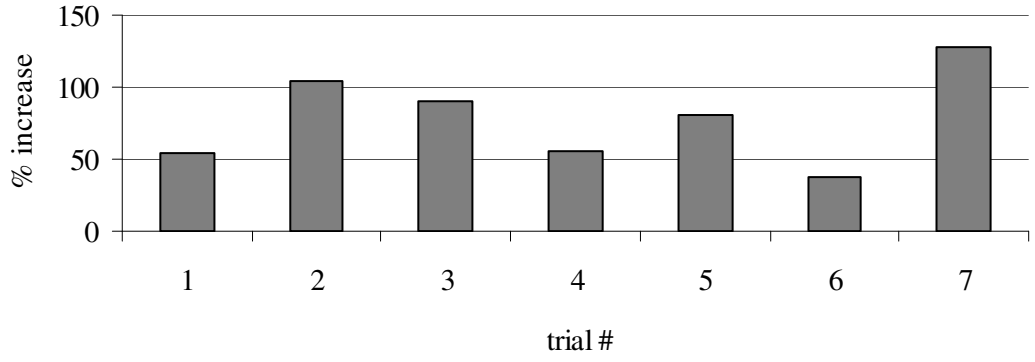

Figure 9.6 Mean variations in TDS over 7 trials

The process of composting 'fixes' nutrients in the solid waste materials [Haug 1993]. This could be one reason for the increased TDS. Nitrification of ammonia into nitrate also increases dissolved solids. As per Fig 9.6, the process cannot be considered repetitive from trial to trial. The small mean increments during trials 1, 4 and 6 point to TDS reductions. These reductions could be a result of slight process changes within the composting mass.

Increase of TDS between the raw blackwater and the primary effluent averaged at approximately 19% while that between primary and final effluents averaged at 36%. There were occasional reductions in the former while the final effluent almost always had a higher TDS. It could be inferred that the treatment of blackwater through vermicomposting did not reduce the dissolved solids but only increases due to release of nutrients. Analysis of cations and anions leading to this could not be conducted due to time, equipment and funding constraints. It has been pointed out in

literature that release of humic and fulvic substances from the composting matrix contribute towards an increase in the final TDS readings [Hänninen *et al.* 2003].

9.3.4 Conductivity

Conductivity is expected to have a similar response to TDS, and it did (Table 9.3). The increased TDS probably accounts for most of the change in conductivity. The mean conductivity value increased over the entire testing period was 69.77% including reductions noted for 3 samples. The variations in conductivity are evident within runs and among trials (Figs 9.7 and 9.8).

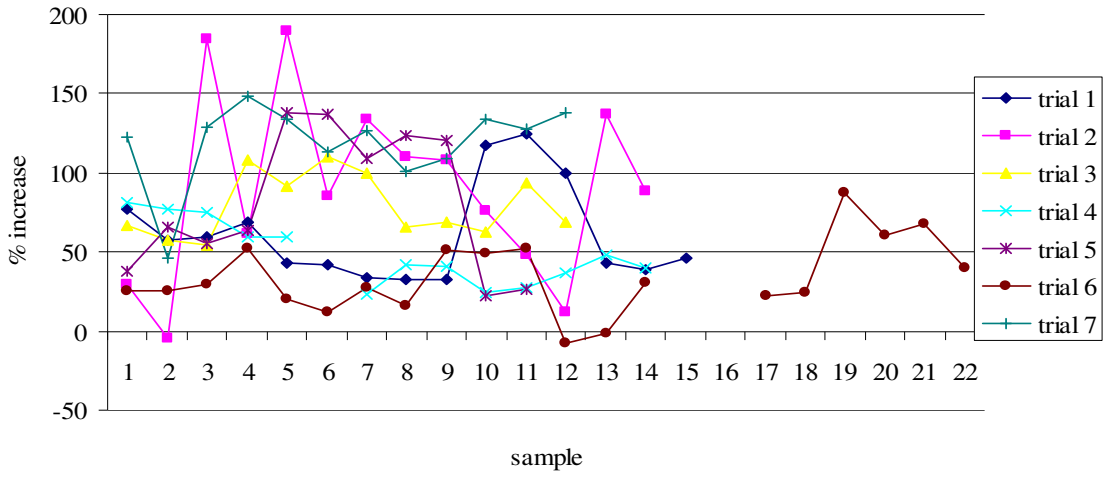

Figure 9.7 Overall variations in conductivity

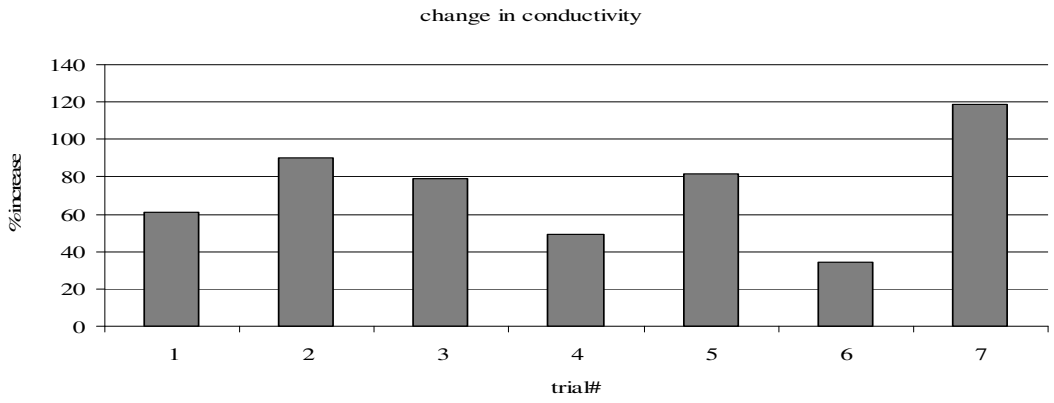

Figure 9.8 Mean conductivity variations for the entire experiment period

An average 21.8% variation between the raw influent and the primary effluent as well as an average 31.35% variation between the primary effluent and the final effluent was observed. Such wide difference within the process indicated that the process did not yield consistency in terms of chemical reactions.

9.3.5 TSS-Turbidity-TDS relationships

In wastewaters, the main factor causing turbidity is suspended solids, the other major factor being precipitates. TSS and turbidity had the same pattern (Figs 9.9a and 9.9b).

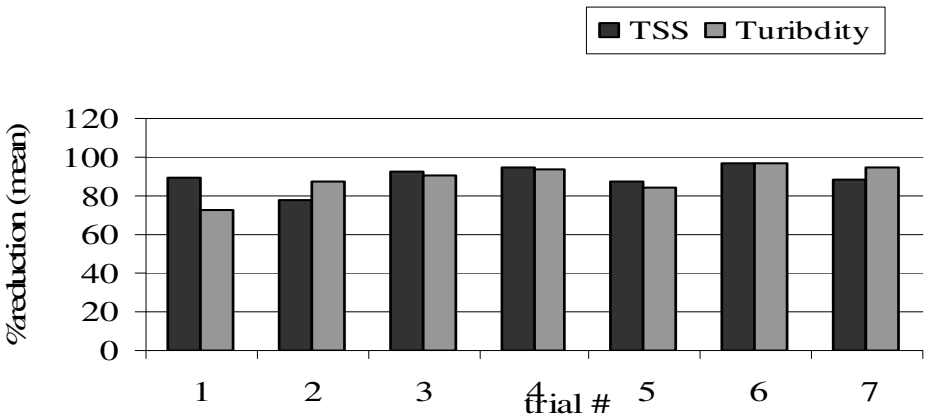

Figure 9.9 (a) TSS-turbidity trends over the testing period

Fig 9.10 gives the relationship between TSS and turbidity for each of the trials separately based on readings for individual samples. It can be observed that both the parameters followed similar variation between influent and effluent to the vermicomposting unit in all the trial runs. The relationship between TDS and turbidity is plotted in Fig 9.11. The reductions in TSS and turbidity followed similar trends while TDS gave no particular trend with the other two parameters, but it could generally be inferred that removal of suspended solids and particulate matter, along with dissolution of some chemical precipitates had reduced turbidity.

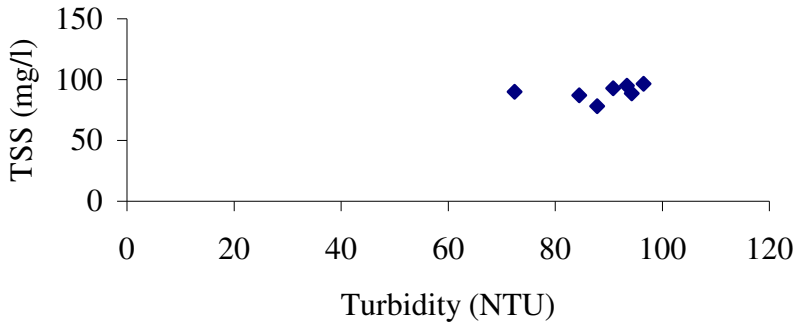

Figure 9.9 (b) TSS-Turbidity relationship

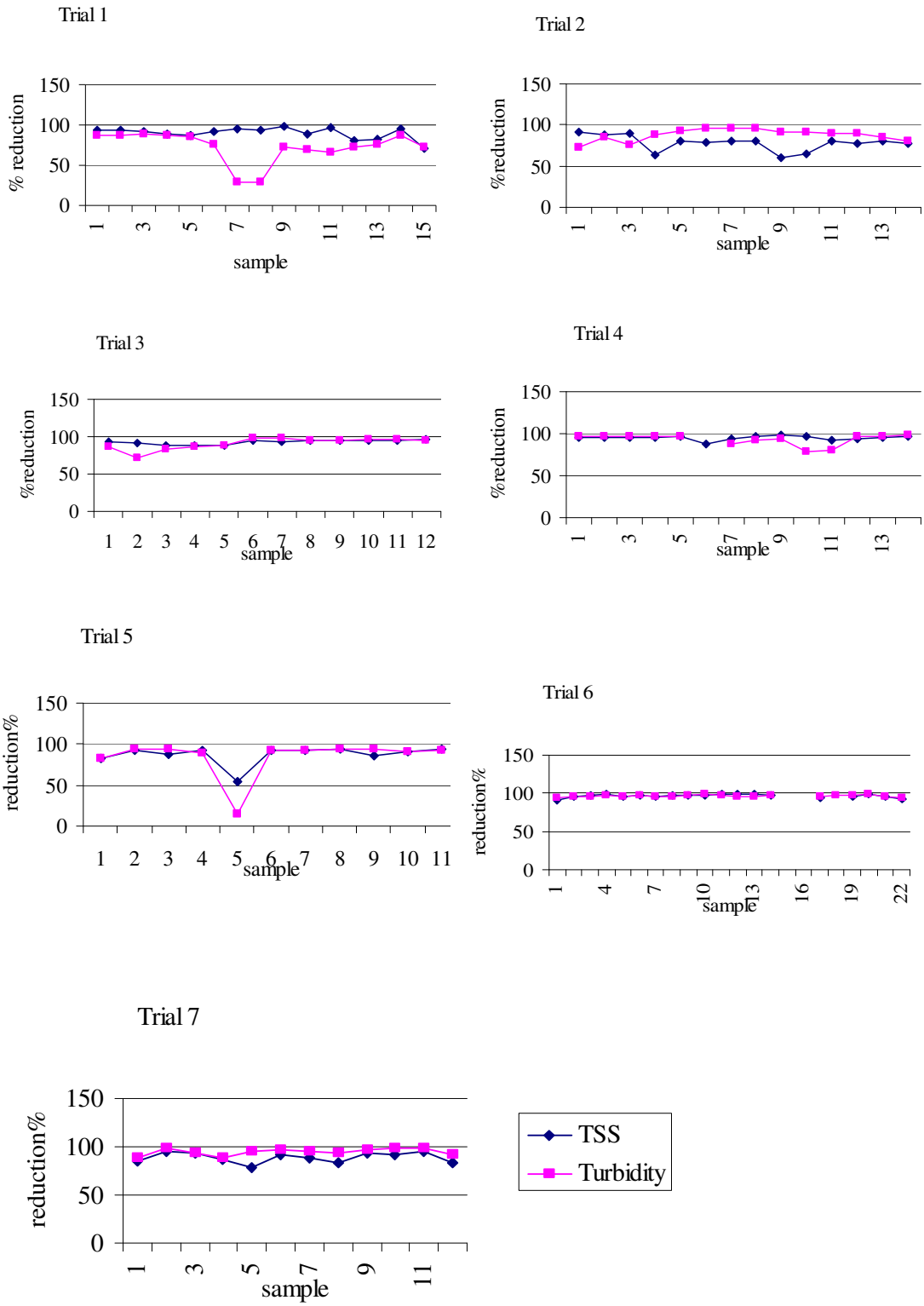

Figure 9.10 TSS and turbidity trends for the individual trial runs

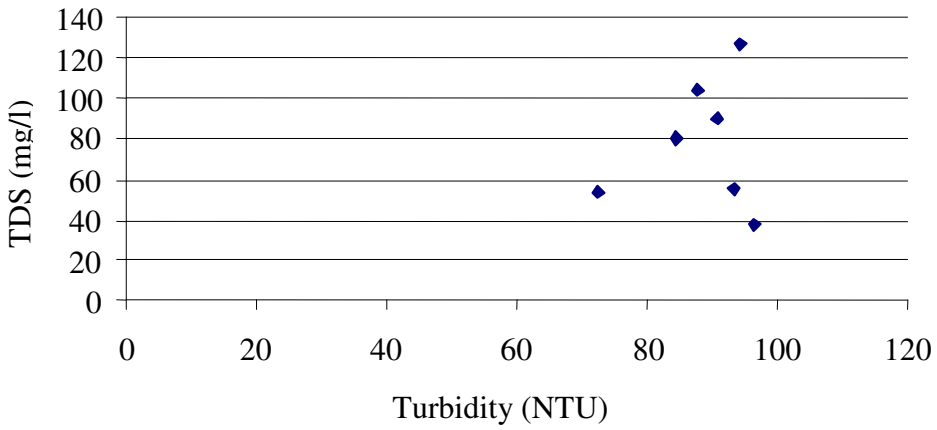

Figure 9.11 (a) Relationship between mean Turbidity and TDS

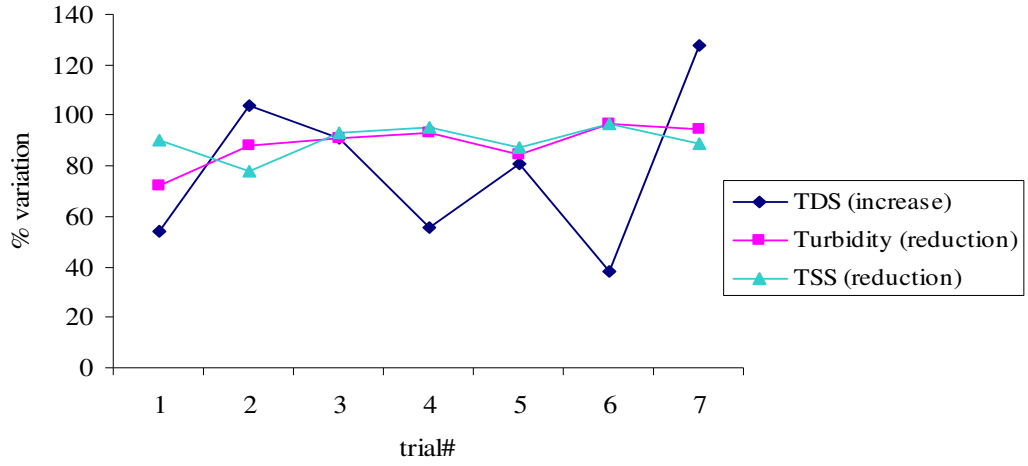

Figure 9.11 (b) Trends – mean TDS, TSS and turbidity

9.3.6 TDS-Conductivity relationship

The amounts of dissolved solids in the liquids and electrical conductivity have a close association as obvious in the graphs Figs 9.12 (a and b) and 9.13. It could be inferred that both parameters followed a closely comparable trend. A detailed analysis of the individual cations and anions of both raw blackwater and final

effluent could give a clear indication of what chemical constituents cause the increased readings of TDS and conductivity.

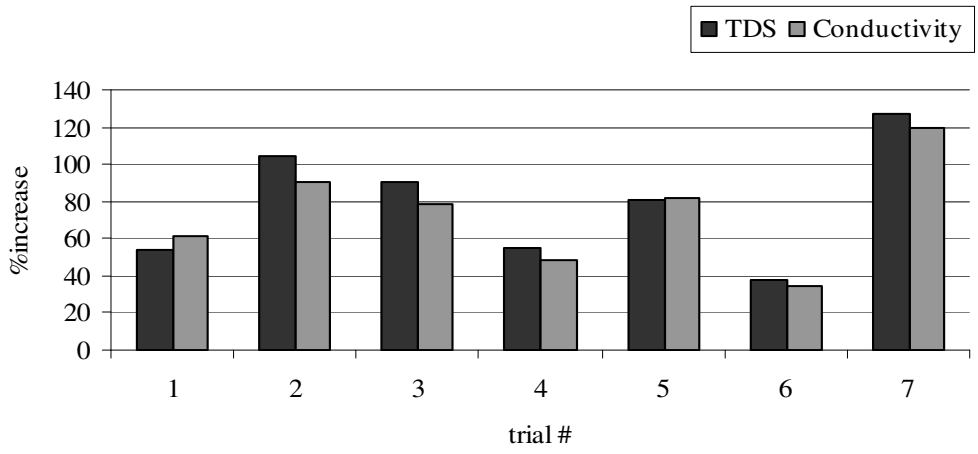

Figure 9.12 (a) Relationship between mean TDS and conductivity of different trials

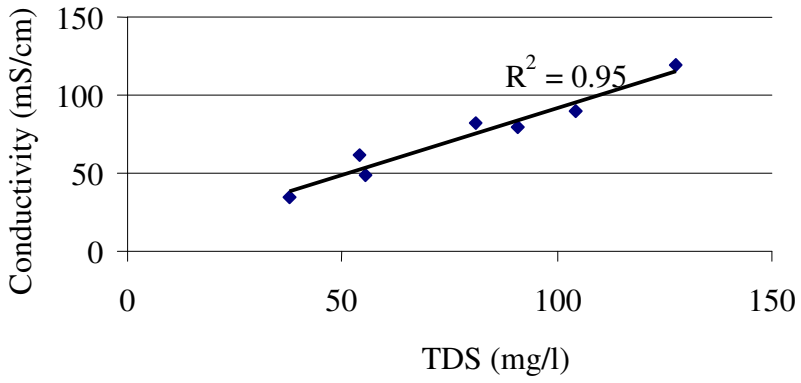

Figure 9.12 (b) Linear relationship between TDS and conductivity

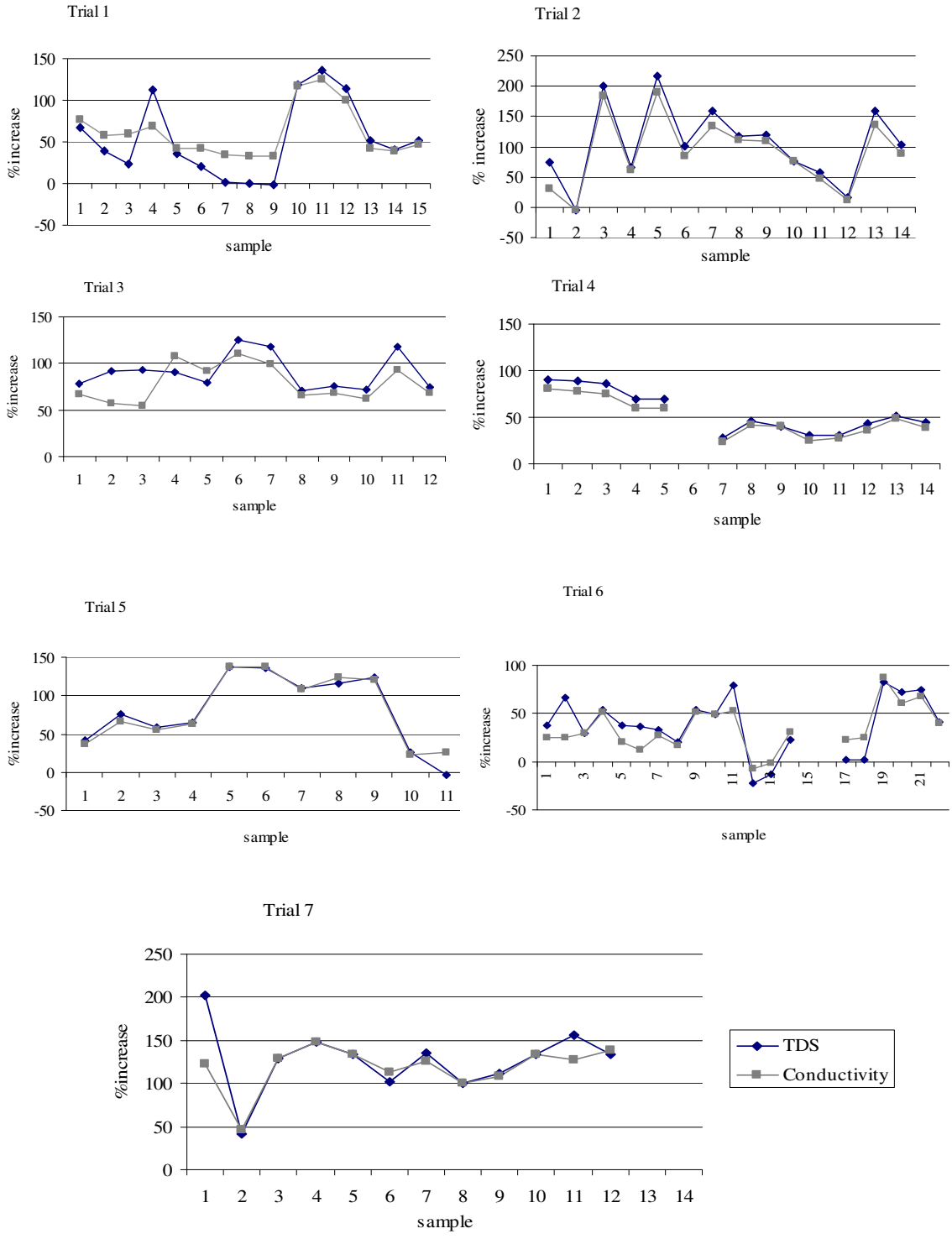

Figure 9.13 TDS-Conductivity trends over the 7 trial runs

9.4 Chemical changes in the processing system

The chemical parameters of interest are Dissolved Oxygen (DO), 5-day Biochemical Oxygen Demand (BOD_5), Chemical Oxygen Demand (COD), nitrogen (ammonium-N and nitrate-N as effects of nitrification reactions) and phosphorous (as reactive phosphorous). Amount of DO gives indication of aerobic conditions within the system. Denitrification reactions occur in anaerobic conditions; therefore reduced DO in effluent would require estimations of Total Kjeldahl Nitrogen (TKN). The percentage variations between influent and effluent are reported.

The raw wastewater characteristics are comparable to earlier findings in literature [Larsen and Gujer 1996]. As expected, the dissolved oxygen content of the wastewater improved while pollutants causing oxygen depletion were seen to reduce (BOD and COD). Toxic ammonia as ammonium-N reduced generally, while nitrate-N and reactive phosphate increased many fold, contributing to the very high TDS readings discussed earlier. The mean variations of each of these parameters with their standard deviations within each trial are given in Table 9.4.

Table 9.4 Mean variations of different chemical parameters within each trial, with standard deviations in parentheses

Trial #	***% DO (increase)***	***% BOD (reduction)***	***% COD (reduction)***	***% NH_4-N (reduction)***	***% NO_3-N (increase)***	***% PO_4-P (increase)***
1 n=15	89.32 (5.65)	95.45 (0.58)	62.33 (6.21)	90.29 (1.87)	193.16 (27.85)	176.97 (58.47)
2 n=13	78.25 (11.47)	95.99 (0.62)	70.30 (0.53)	90.62 (0.66)	104.35 (39.13)	111.27 (33.27)
3 n=12	65.95 (12.03)	97.13 (1.32)	73.46 (0.77)	90.96 (1.45)	275.08 (100.22)	133.37 (18.87)
4 n=14	73.44 (2.42)	97.01 (0.94)	72.19 (1.61)	89.64 (2.86)	120.77 (48.49)	92.61 (6.1)
5 n=11	70.85 (11.37)	97.27 (1.62)	35.14 (7.87)	85.41 (2.12)	207.36 (63.07)	300.17 (36.91)
6 n=22	92.23 (4.02)	98.52 (0.93)	74.97 (10.97)	90.26 (3.21)	567.54 (275.26)	148.94 (97.27)
7 n=14	92.64 (3.82)	97.72 (1.63)	82.42 (3.36)	85.76 (7.14)	1472.4 (1240.76)	224.87 (272.987)

(n is the number of samples in each trial run)

9.4.1 Dissolved Oxygen, Biochemical Oxygen Demand and Chemical Oxygen Demand

Dissolved oxygen increased considerably during the treatment of liquid pig manure through the vermicomposting mass. This increase suggests that the system was aerobic, as planned. The overall mean increase in DO was 80.94%. The highest reading was of 98.21% from an initial 0.09 mg/l DO to 5.03 mg/l DO. The air channels created by worms in the vermicomposting mass had caused enough air passage into the interiors of the system that helped create an ideal environment for themselves and aerating the passing fluid.

The mean variations of individual trials are presented in Fig. 9.14 variations for trials are plotted in Fig. 9.15. The DO of the primary effluent was found to be typically between that of the raw wastewater and the final effluent, with mean

increase of 61.75% from the raw to primary and mean increase of 44.99% from the primary to the final effluent samples. It could be inferred that most of the treatment occurs in the early stages itself where worms are more active (thus more air channels) with fresh waste.

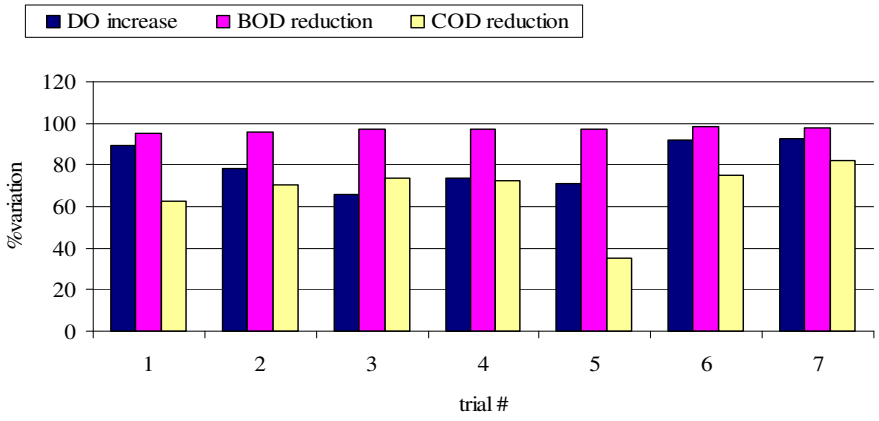

Figure 9.14 (a) Overall mean variations of DO, BOD_5 and COD

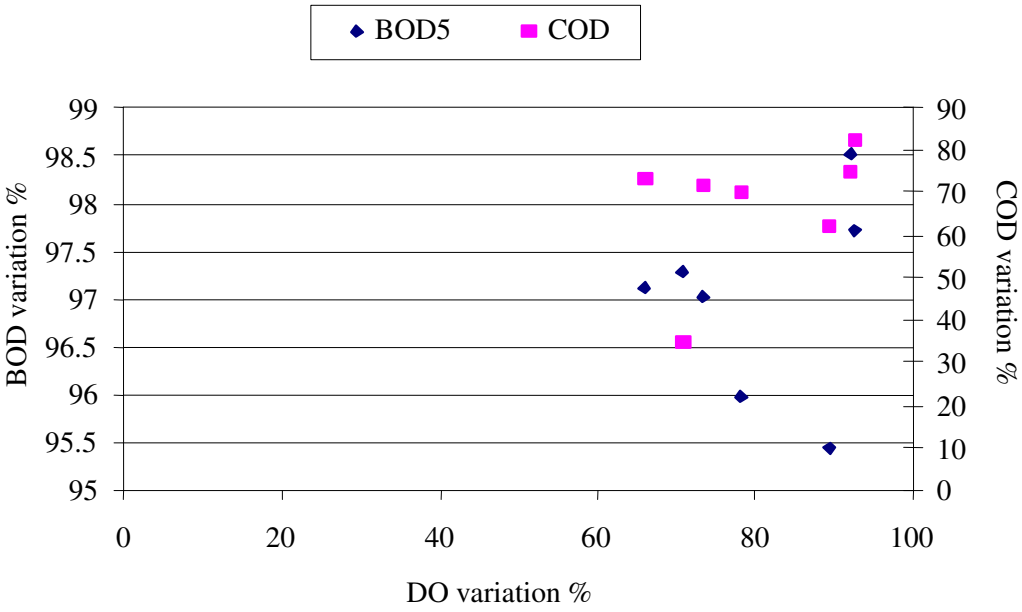

Figure 9.14 (b) Relationships of BOD-DO-COD for the seven trial runs

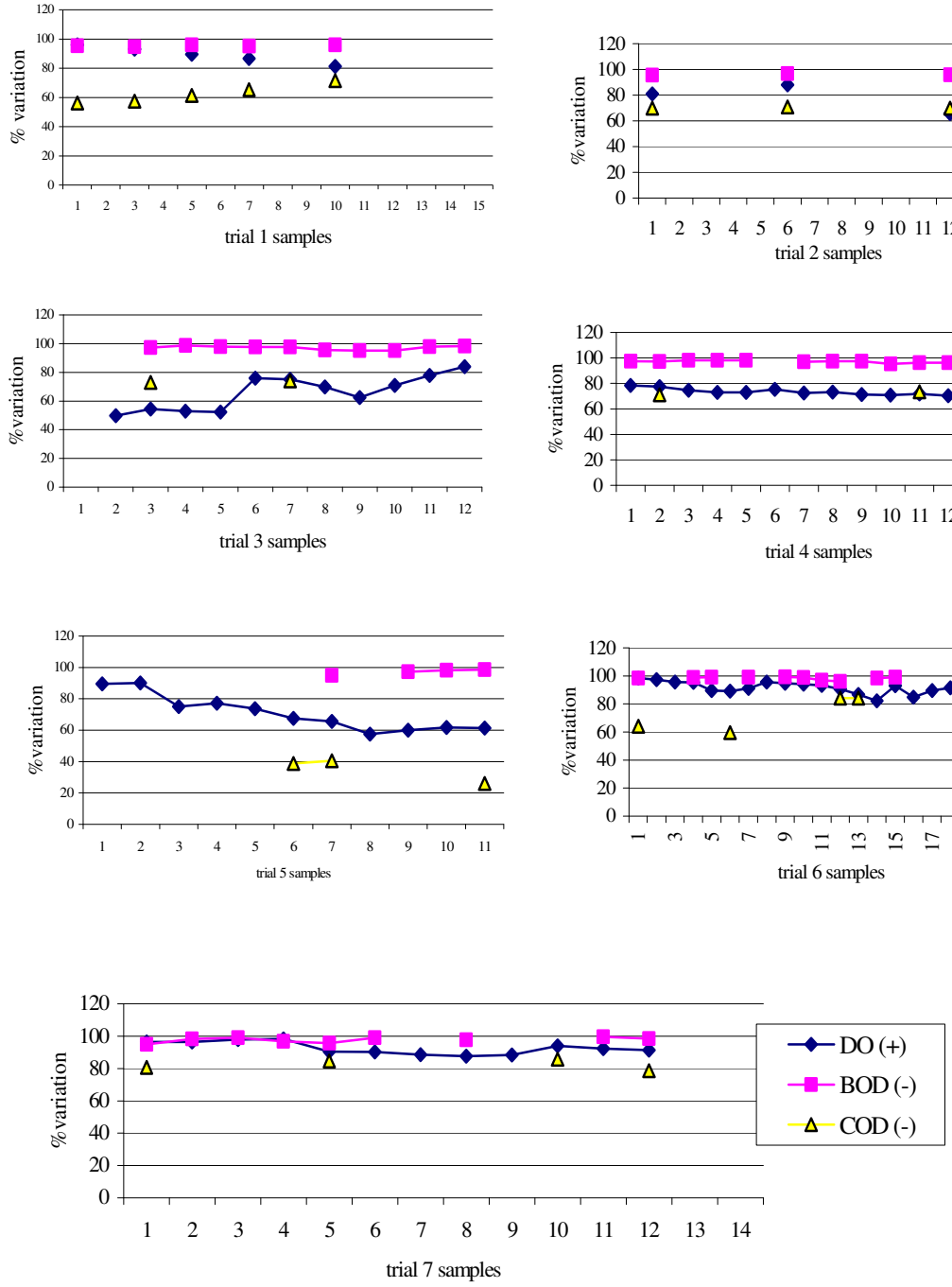

Figure 9.15 DO-BOD_5-COD variation trends for individual trials

BOD_5 reductions were considerable between the raw pig manure and the treated final effluent. An overall average reduction of 97.49% was reported between raw and final effluent, with raw BOD_5 of 5000 mg/l reduced to 75 and 1600 to 10 mg/l. The mean reductions over the different trials are plotted in Fig 9.14 and reductions in the individual sample batches in Fig 9.15. The reductions stayed in the 90-100 % range, giving BOD_5 values as low as 5 for the treated effluent (from 1300 mg/l for raw, 99.62% reduction), showing that the treatment by vermicomposting worked well.

The BOD_5 reductions from the raw blackwater to the primary filtrate averaged 80.5% while that between primary and final effluent averaged at 79% with less than a standard deviation of 2. The final BOD_5 readings for the effluent compared with greywater-BOD readings in the literature.

The surroundings of the prototype and the treated samples did not have obnoxious odours during the entire testing period. The raw samples had very objectionable odour, the primary effluent had slight earthy/oily smell while the final effluent did not have anything more than the smell of the moist compost itself.

Chemical pollution load, measured as chemical oxygen demand (COD), showed considerable reductions. The overall mean reductions of all seven trials are given in Fig 9.14 while individual reductions for each trial are given in Fig 9.15. The averaged COD reduction was 69.67% with the highest raw COD reading of 13000mg/l reduced to 2000 mg/l (reduction of 84.62%). As the vermicomposting proceeded with high humidity levels, no temperature increase was noted, as reported in literature for microbial composting [Haug 1993]. Proper aeration was another

factor that contributed to good COD removal. The mean COD value of raw pig manure was 5901.6 mg/l and that of the final effluent was 1517.7 mg/l. An average 47% COD reduction was noted for the first stage (raw blackwater to primary effluent) and 39.75% reduction for second stage (primary effluent to final treated effluent).

Increase in DO somewhat corresponded to reductions in BOD_5 and COD values (Fig 9.14). The mean COD/BOD ratio of raw wastewater was approximately 2.85:1, which is well within the range given in literature [Aalbers 1999] while that of treated effluent was 26.89:1. Reductions in the organic pollutant content were consistent and gave comparable results between all the trial runs. The final effluent gave readings comparable to greywater [Shin *et al.* 1998; Surendran and Wheately 1998; Lindstorm 2000a; Craven and Davison 2001; Eriksson *et al.* 2001].

9.4.2 Nitrogen and Phosphorous

Transformation of nitrogen from ammonia into nitrate was evident in the vermicomposting prototype. The mean reductions in ammonium-N content and mean increases in nitrate-N during the individual trial runs are given in Table 9.4. An average 88.82% reduction in ammonium-N was observed for the entire testing period with the highest reduction of 97.33% (from 1500 mg/l NH_4-N in the raw blackwater to 40 mg/l in the final effluent) during trial 7.

However, the increase in nitrate for the same sample batch was not correspondingly high, over 671% (the overall mean nitrate increase 636.94%). The highest nitrate increase noted was 64 fold, the next closest increase being 28 fold. Variation in

nitrate between raw and final samples was not consistent, though the high increase points to high nitrification rates. As discussed earlier, an increase in DO favoured only aerobic reactions, therefore denitrification reactions were not significant. The mean and detailed variations in the different trials for ammonium-N and nitrate-N are plotted in Figs 9.16 and 9.17.

Reduction of ammonium-N showed consistency over the different trials. The mean reduction of ammonium-N between the raw wastewater and the primary effluent was 64% while that between primary and final effluents were 64.35%. This showed a consistent first stage nitrification regime throughout the vermicomposting mass in the prototype. However, the corresponding % increments for nitrate were 300.63% and 39.98%, showing that nitrate-formation occurred mostly during the primary filtration stage.

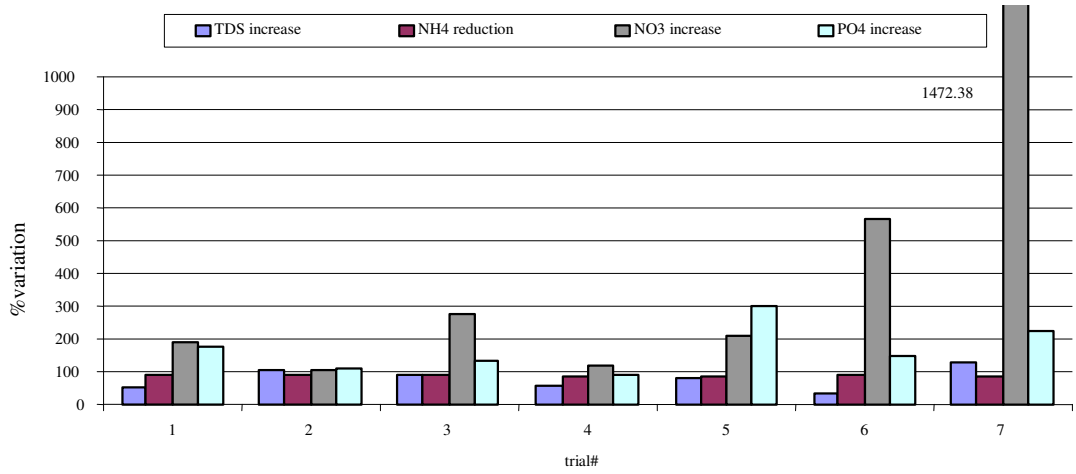

Figure 9.16 Variations in TDS, ammonium-N, nitrate-N and P (phosphate)

Phosphorous content, as reactive phosphate, also increased averaging at 182.58% over the entire testing period. The increase ranged between 33.33% (raw 1200 mg/l PO_4^-; effluent 1600 mg/l during trial run 7) and 715.79% (raw 190 mg/l; effluent 1550 mg/l – same trial). The variation between raw and primary effluent averaged 88.81% while that between primary and final treated effluent averaged at 51.75%. The transformation of P is not very consistent. The lower readings for the different stages of filtration might also be due to the lower number of primary samples analysed.

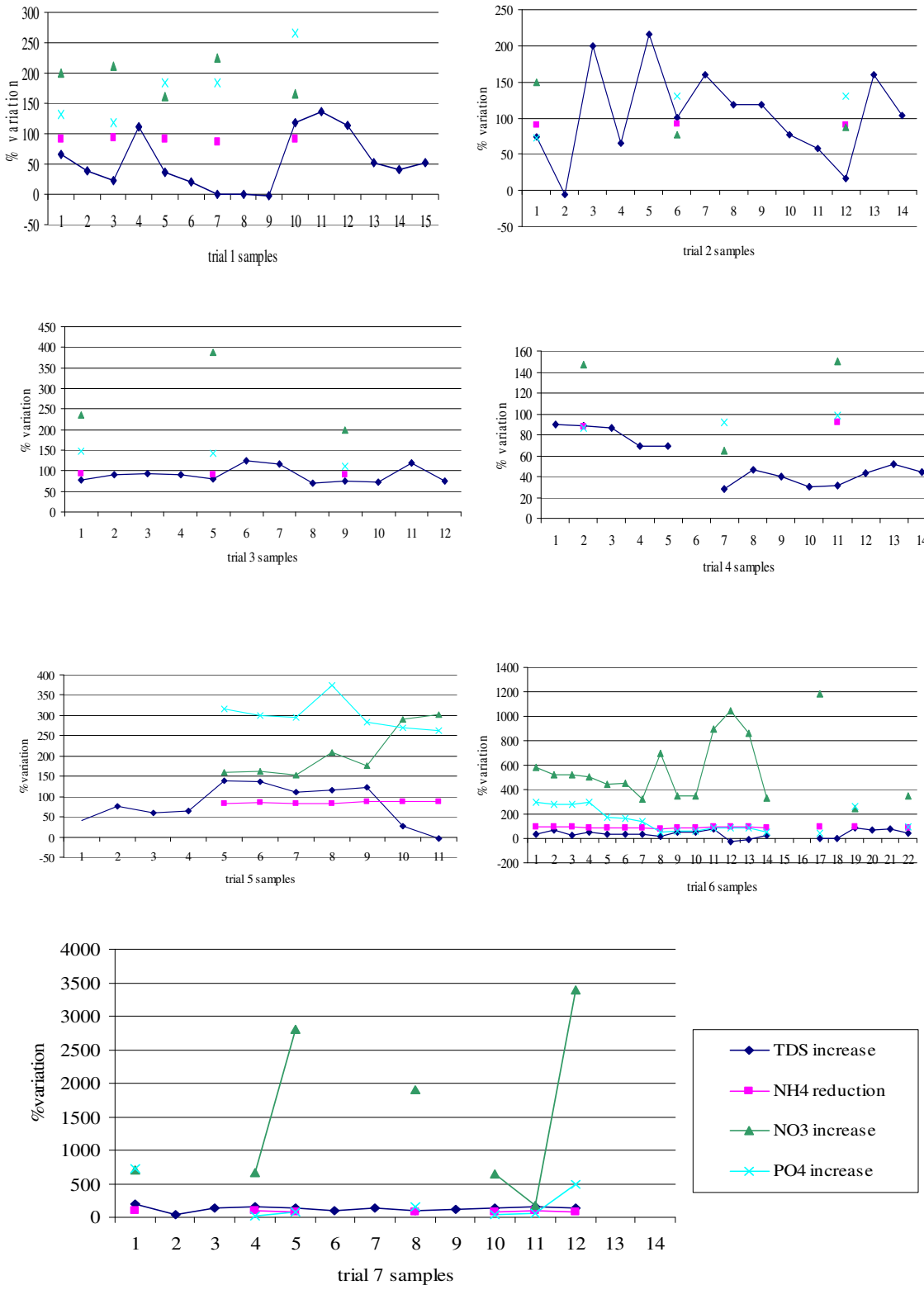

Figure 9.17 Variations in TDS, nitrogen and phosphorous for the seven trials

9.4.3 pH

The influent (blackwater) was slightly basic pH (7.25 – 8.96 range) due to the high pH of pig manure and perhaps due to washing solutions used at the piggery. The pH declined during filtration through the vermicomposting medium. The filtrate had a pH range of 4.728 – 6.44. The primary effluent had a rather neutral pH range of 6.243 – 7.85. This showed that the reactions that caused pH reduction occurred throughout the medium. The other constituents in the wastewater could also contribute towards the pH ranges and the water itself could dilute them.

The pH of the liquid effluent reflects the pH of the medium through which it was filtered. Release of H^+ ions by nitrification reactions could cause lower pH in composting medium [Sánchez-Monedero *et al.* 2001]. Other causes could be production of humic and fulvic acids during composting. It has been shown that a very low pH (<4.5) in the liquid could indicate that the solid materials have not undergone complete degradation [VanderGheynst 2003]. But the pH ranges in this project did not show such low ranges for extended periods. As anaerobic conductions were not detected, presence of other organic acids associated with waste degeneration could not be considered critical.

Fig 9.18 shows the pH variations of the seven trial runs. It could be inferred from the graphs that the pH ranges were comparable among the different trial runs. Within each trial run, the variation of pH of both influent and effluent remained stable. This points to the inference that the reactions that caused the lower pH in the final effluent had remained consistent. As pH variation is caused mainly by release of H^+ ions

during nitrogen fixing reactions, this observation could be read along with steady ammonia reduction.

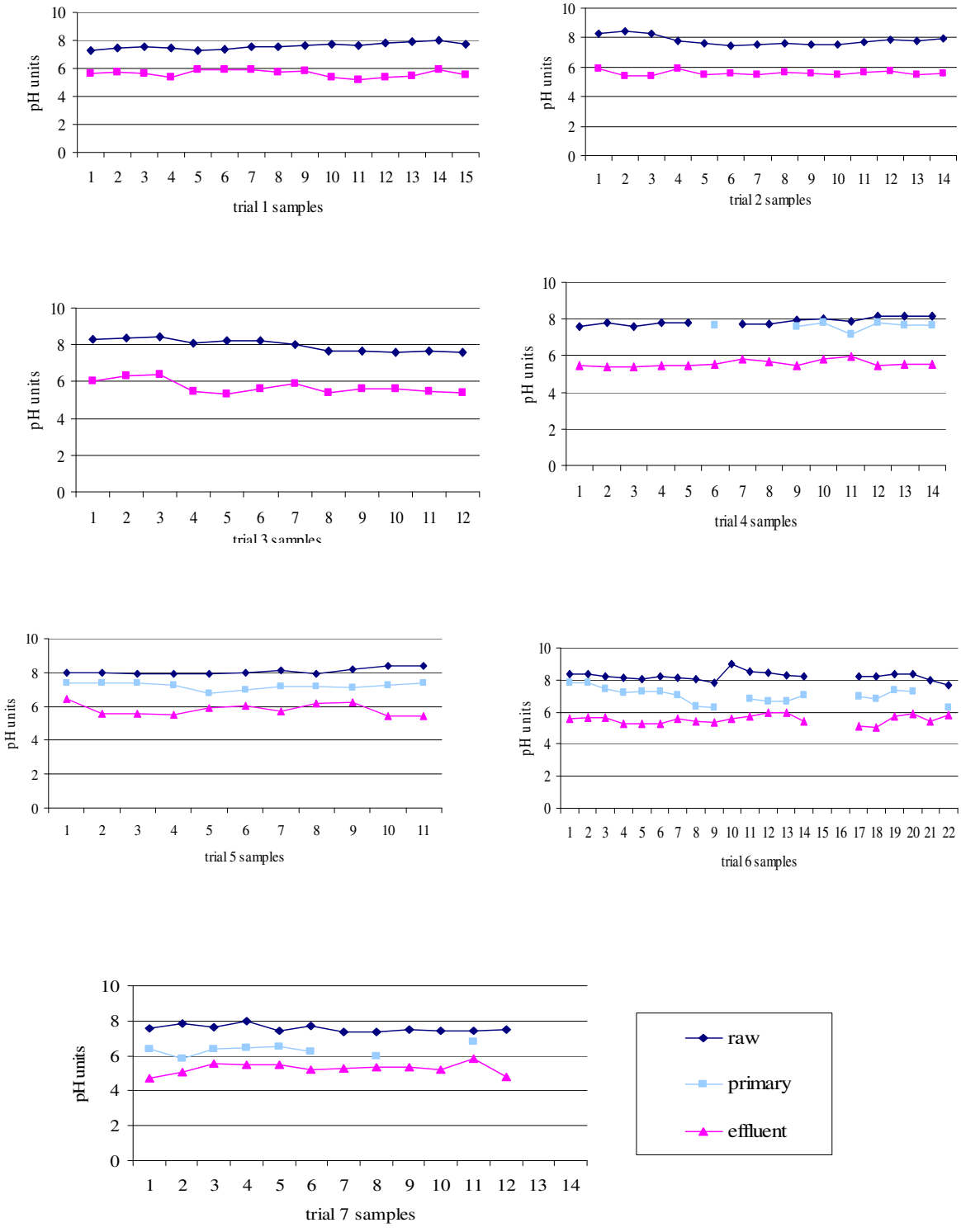

Figure 9.18 pH variations for individual trial runs

9.5 Biological Parameters – faecal coliform and *E. coli*

Faecal coliform and *E. coli* were found to decrease considerably during the test period. The analysis results were reported as CFU/100ml, but as the input quantities varied widely the decrease as log-reduction or orders of magnitude was of interest. It was found that an overall mean of two orders of magnitude reduction was achieved for faecal coliform and for *E. coli*. Table 9.5 provides the mean log reduction values and standard deviations for individual trial runs in regards to pathogen reduction. Fig 9.19 shows the trial-mean log reduction in both the microbiological parameters for the entire testing period.

Table 9.5 Mean orders of magnitude reductions in faecal coliform and *E. coli*

Trial #	*Faecal coliform*		*Escherichia coli*	
	Log reduction	***Std. dev.***	***Log reduction***	***Std. dev.***
1 (n=15)	0.63	0.33	0.64	0.32
2 (n=13)	1.51	0.96	1.50	0.93
3 (n=12)	2.21	1.41	2.14	1.33
4 (n=14)	1.58	0.72	1.71	0.64
5 (n=11)	0.80	0.90	0.81	0.95
6 (n=22)	2.38	1.15	2.35	1.09
7 (n=14)	2.33	0.58	2.28	0.53

(n is the number of samples in each trial run)

The average orders of magnitude reduction for faecal coliform and *E. coli* between the raw wastewater and the primary effluent were both 1.12 whereas the readings between primary and final effluents were 1.00 and 1.09 respectively. It could be

inferred that the pathogen reduction achieved during the initial stages and the final stages of filtration of blackwater through the vermicomposting matrix in the prototype were generally consistent. Reduction in the indicator organism was slightly higher than total faecal coliform counts.

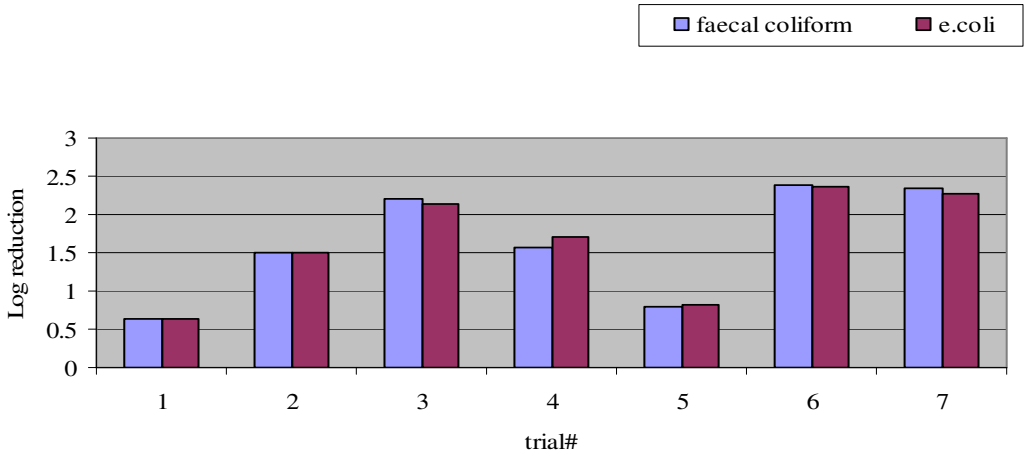

Figure 9.19 Log reduction of faecal coliform and *E. coli*

It could be seen that the two trials with comparatively poor microbiological reductions (less than 1 order of magnitude) were the initial trial and the trial 5 where a period of one month without monitoring occurred. The other trials reported reductions averaging two orders of magnitude. The final effluent had counts of 100 CFU/100ml in a majority of occasions while the raw influent had correspondingly high counts of pathogens (Fig 9.20). The overall (raw to final effluent) pathogen reduction ranged between zero for very few sample batches to five orders of magnitude (*E. coli* five) during trial 6. The low reductions were mostly for sample batches with raw samples containing very low counts of pathogens, perhaps due to any chlorine disinfection effected through the wash water used in the piggery. It was not possible to identify the chlorine content, as the wash times and the quality of the

water used at the piggery from where the pig manure was collected were not consistent.

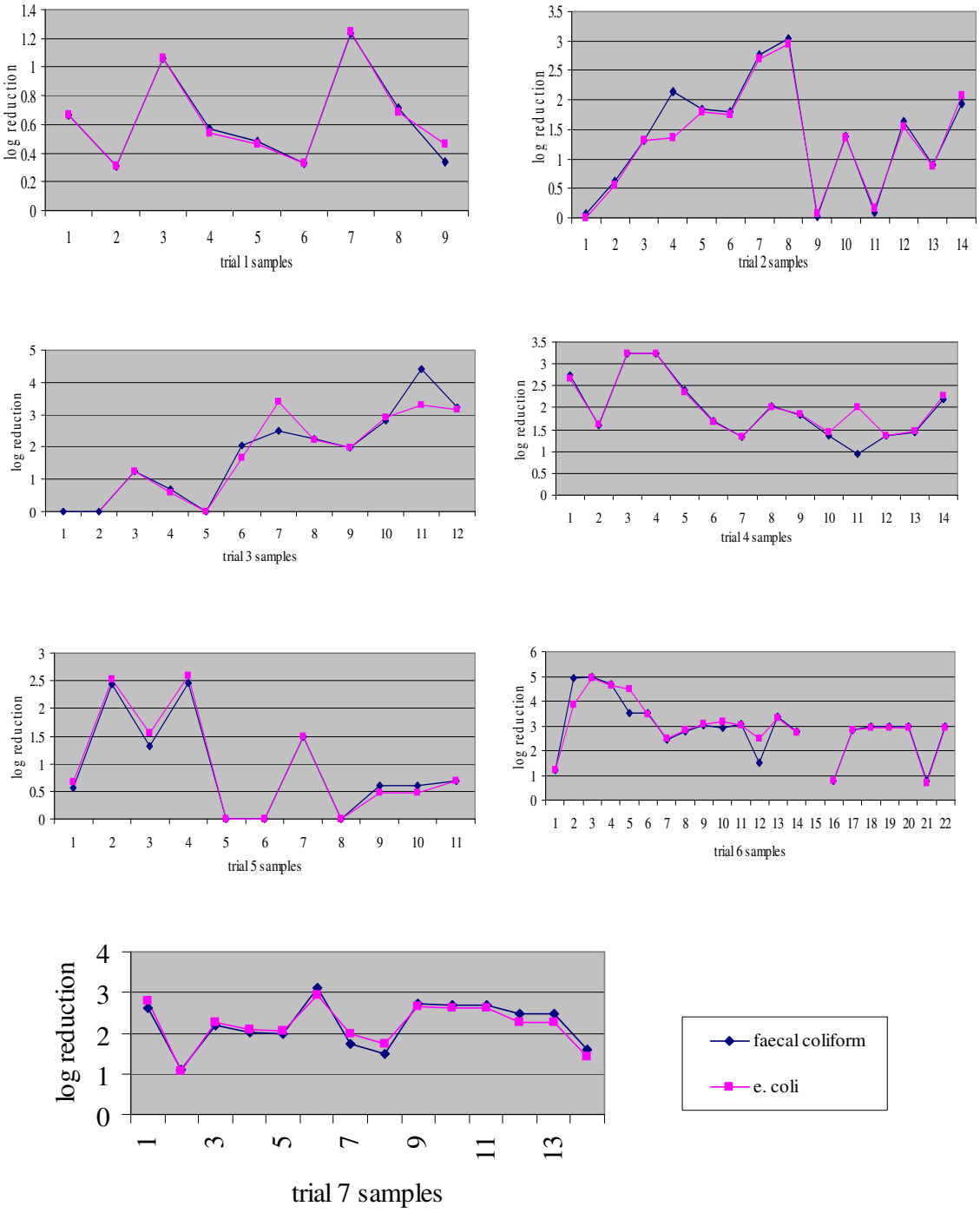

Figure 9.20 Log reduction in faecal coliform and *E. coli* for different trial runs

9.6 QA/QC Results

The quality assurance/control aspect of this project included duplicates, blanks and spiked samples. Duplicates were tested on alternative equipments on a monthly basis and results between analyses were consistent. For BOD_5, in-house testing on two different instruments (Oxitop® and Oxidirect®) gave uniform results. All parameters were tested on alternative instruments for intra-laboratory comparison and found to not significantly differ. Occasional shock loads were applied as mentioned earlier in this chapter in the form of double influent load. The system was able to accommodate such spikes.

Two samples from the trial 7 (sample 160 at the start of trial 7 and sample 171 at the end of trial 7) were sent to Barrett and Smith Laboratories (BS) for professional analysis. This gave inter-laboratory comparison. Some parameters gave very consistent results as with the intra-laboratory comparison set; while nitrate readings in the raw samples differed. This was due to the very high turbidity of the raw samples [Bob Sinclair, chemist, Barrett and Smith Laboratories, *personal communication*]. The inter-laboratory comparison results are given in Table 9.6.

Earlier attempts to use another laboratory for inter-laboratory QA analysis yielded similar results as the Barrett and Smith labs. Cost and time constraints prevented analysis of diluted samples at this laboratory. Nevertheless, the evidence is that the in-house testing of different physical and chemical parameters gave reliable results. As microbiological analysis was done at NATA accredited Australian Government Analytical Laboratory (AGAL), no further QA analysis was conducted on

microbiological parameters. The in-place quality control programme at the AGAL gave assurance that the results were reliable [Newton 2003].

Table 9.6 Inter-laboratory comparison results

Parameter	**160**	**160 BS**	**160b**	**160b BS**	**171**	**171 BS**	**171b**	**171b BS**
pH	7.538	7.3	4.728	4.9	7.48	7.5	4.8	4.6
Conductivity (mS/cm)	5.462	5.16	12.464	13.6	4.98	5.5	11.855	12
Turbidity (NTU)	2062	1250	246	250	3580	2130	311	270
TSS (mg/l)	3800	1800	600	670	3500	3600	580	530
TDS (mg/l)	3199	3720	9680	9920	3800	3950	8870	8790
DO (mg/l)	0.27	0.3	7.55	8.2	0.45	0.4	5.2	3.7
BOD5 (mg/l)	3500	3800	180	240	5000	5900	75	90
COD (mg/l)	8000	6500	1740	1900	7400	7000	1588	1600
NH3 (mg/l)	750	460	80	75	600	530	80	30
NO3 (mg/l)	650	10	5300	5600	100	13	6500	6820
PO4 (mg/l)	190	170	1550	1320	300	170	1800	2050

Samples with ID 160 and 171 were in-house testing on raw samples; 160b and 171b were in-house testing on final effluents while 160 BS, 160b BS, 171 BS and 171b BS were tested at the Barrett and Smith Water Testing Laboratory.

9.7 Conclusions

This chapter presented the results of blackwater (liquid pig manure) treatment by filtering through the vermicomposting prototype, the design of which was presented in the previous chapter. Variations in physical parameters (TSS, turbidity, TDS and conductivity), chemical parameters (pH, DO, BOD_5, COD, ammonium-N, nitrate-N and phosphate) and microbiological parameters (faecal coliform, *E. coli*) were presented and discussed. Overall variations in these parameters were presented as charts. The results of inter-laboratory quality control measures were also presented.

Turbidity was reduced to levels comparable to greywater. It was observed that while particulate matter and solids were filtered in the vermicomposting matrix, dissolved solids and nutrient content (nitrate and phosphate) increased many fold. The pH of the liquid waste, as it passed through the unit, changed from basic to acidic possibly due to release of hydrogen ions and humic acids from the composting process. The source of this excess hydrogen ions were probably the strong nitrification reactions taking place within the test unit, converting ammonium-N into nitrate. Reduction in ammonium and increase in nitrate were large, confirming the assumption of the cause for the pH variation.

Dissolved oxygen content in the liquid increased many fold. This indicated that the process was almost free of anaerobic reactions, and therefore denitrification reactions were not of concern in this project. The DO content of the final effluent was close enough to the levels that are safe for natural waterways. Lack of any objectionable odour at the site and in the liquid effluent was also evident. Reduction in BOD_5 and

COD was also considerable, the former giving very satisfactory results. The 5-day BOD readings for the final effluent were within the greywater-BOD ranges.

Up to 4 orders of magnitude reductions of pathogen count were achieved through the process. This was considered satisfactory, considering that the effluent would undergo further treatment along with greywater in the next phase of the project. The testing procedures met QA/QC guidelines.

Generally, the treatment of the blackwater in the prototype vermicomposting unit was excellent. The results of solid waste degradation are presented in the next chapter.

CHAPTER 10 DEGRADATION OF SOLID SUBSTRATE IN THE PROTOTYPE VERMICOMPOSTING UNIT

10.1 Introduction

The solid waste matrix within the vermicomposting unit undergoes changes resulting from the actions of microbes, worms and other organisms within the system. Several transformations take place, such as the particle size, mass, volume, structure, moisture content, water-holding capacity, nutrient-content (N & P), pH, C: N ratio, pathogen count and appearance change for the solid matter. This chapter examines the transformation of some of waste based on the tests conducted on the prototype vermicomposting unit.

Several parameters describe the waste material. Other than the critical ones identified above, there are other parameters that may be used to describe the waste and the transformations that it undergoes. Such parameters as heat generation, gas production, organism content and quantity (numbers, mass) are not addressed in this thesis because they were not considered essential to understanding the dynamics of the waste transformation, and (usually) because their inclusion would represent a major effort in measurement with questionable return for the objectives of this thesis. This does not mean that they are insignificant, and their study should be the matter for future studies of waste management using vermiculture.

10.2 Materials and Methods

The physical and chemical transformations were analysed using an input-output model approach, that is, examining the variation between the input of waste material and the final solid residue (vermicastings). An input-output approach lends itself to developing budget models for the waste system without having to measure, describe and investigate the details of the dynamics and kinematics of the processes operating within the waste system. The changes in inputs and outputs were observed over seven composting cycles using similar substrate content, prepared according to the "standard" composition detailed in chapter 8. The vermicomposting unit was cleaned between cycles, after the removal of residues of the earlier cycle and prior to filling with new material. Only the bedding material was prepared from mature castings and partly degraded material (used as recycle) to assist the worms to acclimatise with the 'new' environment within the unit.

Standard test methods as prescribed by Appendices A, H, I, and O in the Australian Standard AS4454-2003 (Composts soil conditioners and mulches) were utilised for measurement of different parameters. The vermicasts cleaned after each composting cycle were tested for pH, total dissolved solids, conductivity, ammonium, nitrate and phosphate content, moisture content, faecal coliform and *E.coli*. Most of these tests were conducted on liquid extracts of the solid vermicasts as described in the above Standard and results presented in units of mg/L of extractant, as prescribed in the Standard (Appendix A of AS4454). Test methods are given in Appendix III. Daily measurements of temperature of the substrate within the top chamber as well as the lower chamber were taken (in-situ) using a bimetallic thermometer and a methanol-filled long stem thermometer. Pathogen content was measured at Australian

Government Analytical Laboratory (AGAL) where liquid samples were also analysed.

Measurement of C: N ratio could not be done due to unavailability of instruments for TOC (total organic carbon), TOM (total organic matter) and TN (total nitrogen). Otherwise, the same instruments that measured the different parameters in the liquid samples were utilised in the measurement of relevant parameters (pH, nitrate, ammonium, phosphate, conductivity and TDS in the extractant) of the solid samples using the test methods prescribed by Australian Standard AS4454 (given in the next sub-section) at the end of each composting cycle. Quality control/assurance measures were similar to liquid sample analysis, mentioned in chapter 9.

In most cases solid residues were removed on Mondays following the end of the composting cycle (which lasted approximately 6 weeks). Excess moisture content could be avoided with a Monday sampling as no liquid waste was added on weekends. Once the unit was cleaned, the worms harvested from the compost removed from the treatment system were placed on 15cm thick bedding material prepared from mature castings of previous composting cycles. Fresh material was added on top in the V-hopper compartment of the prototype. Material removed from the top chamber was added to the top of the bedding in the lower chamber. Blackwater (pig manure) was added on the following day, allowing time for the organisms to acclimatise.

10.3 Results and Discussions

The solid residues were compared to the raw input waste materials for weight and volume reduction. Mass loss as volatile solids (gas) were disregarded in this study, as only the 'visible' material was measured. The results for solid matter transformation are given in Table 10.1(a). Table 10.1(b) presents mass and volume reduction analysis. Sample calculations for trial 7 (composting cycle 7) are given below.

Sample Calculations - Trial 7 (Composting cycle 7):

Percent moisture content in the final vermicast was found out as per the following:

Mass of weighing dish, m1 = 29.69 gm.

Mass of weighing dish + 250ml vermicastings, m2 = 125.18 gm.

Mass of dish and castings after drying at 105^{o}C, m3 = 64.83 gm.

% Moisture content = ((m2-m3)/(m2-m1))*100

= 63 %

The input solids dry weight was calculated as the sum of daily additions for each trial run. The solid content added from the addition of blackwater was calculated from the TSS readings for the blackwater for each trial run. The sum of these two readings gave the total input solids weight. At the end of the composting cycle, the harvested vermicast was weighed and noted as the final weight. The percent mass reduction was then calculated, for each trial run, as per:

% Mass reduction = ((input weight - final weight)/input weight)*100

% Mass reduction for trial 7 = ((25.124 – 15.47) / 25.124) *100

= 38 %

Table 10.1(a) Measurements on soluble extracts of vermicastings

Cycle #	**pH**	**Conductivity (mS/cm)**	**TP (mg/l)**	**Nitrate (mg/l)**	**NH_3 (mg/l)**	**TDS (mg/l)**	**F.C. (CFU/100ml)**	***E.Coli* (CFU/100ml)**	**Casts % moisture**
1	5.91	2.24	80.5	1920	3.58	1870	<100	<100	65.5
2	6.36	2.97	92.2	1850	3.29	1490	<100	<100	58.8
3	5.96	2.36	110	1100	2.7	1320	<100	<100	55.5
4	5.89	2.08	98.9	856	3.11	1350	140	130	60.8
5	6.08	1.85	105.5	950	2.75	1420	<100	<100	65.3
6	5.68	1.76	110.8	680	2.88	1290	<100	<100	62.5
7	5.8	1.28	108.5	257	2.69	1151	<100	<100	63.2
Average values:	5.95	2.08	100.9	1087	3	1413			61.7

Table 10.1(b) Mass and volume reduction

Cycle #	Input solids (Kg)	Solids from blackwater	**Total input weight (kg)**	**Final weight (Kg)**	**% Mass reduction**	**Casts density Kg/m^3**	**Input volume m^3**	**Final volume m^3**	**% Volume reduction**
1	40	0.262	40.262	26.5	34.181	408	0.224	6.50E-02	71.004
2	32.5	0.099	32.599	20.25	37.882	398	0.182	5.09E-02	72.044
3	30	0.087	30.087	18.47	38.612	390	0.168	4.74E-02	71.810
4	32.86	0.123	32.983	17.55	46.791	401	0.184	4.38E-02	76.216
5	27.5	0.111	27.611	20.08	27.275	386	0.154	5.20E-02	66.220
6	26.5	0.412	26.912	17.75	34.044	380	0.148	4.67E-02	68.524
7	25	0.124	25.124	15.47	38.425	382	0.14	4.05E-02	71.073
Average values:	30.62	0.174	30.797	19.44	36.74	392.15	0.17	0.0495	70.985

[Ref: Australian Standard on Composts, Soil conditioners and Mulches AS4454-2003]

A known volume of sample (250ml) was weighed to find out the mass. The density of the vermicast was calculated by finding out the ratio of mass to volume.

Mass of 250ml (m2-m1 above) = 95.49 gm/ 250ml

➔ 381.96 gm/L ~ 382 kg/m^3

The volumes of input substrate were added to find out the total input volume (v1). The ratio of density / total final weight gave the total volume of vermicast (v2). The percent volume reduction: {(v1-v2)/v1}*100

= {(0.14 – 0.0405) / 0.14}*100

= 71 %

An average 37% mass reduction and 71% volume reduction were achieved from the prototype vermicomposting unit. Generally, the mass and volume reductions achieved in composting and vermicomposting depends on the raw waste material. In composting, presence of bulk material such as non-degradable wood chips cause lower volume reduction compared to vermicomposting that lack such bulking materials. Mass reduction occurs due to release of volatile components while volume reduction occurs due to particle size reduction. The highest mass reduction achieved in vermicomposting reported in the cited literature was of 68% [Aalbers 1999]. The average volume reduction reported in microbial composting, in literature, was 50% [Seki 2002] while that of vermicomposting was more. Composting toilets not treating organic MSW have reported a higher volume reduction of 80% [Stauffer 1998]. In light of this, the reductions achieved in the prototype vermicomposting unit were good.

An average pH of 5.95 was measured of solid residues. This could be regarded a 'healthy' pH for vermicompost, as a pH< 5 would indicate that the compost is not stable and one which probably contains phytotoxic compounds [VanderGheynst 2003]. A high electrical conductivity (EC) has been related to unstable composts. The castings from the prototype, with an average EC of 2.08 mS/cm over the 7 trial runs, could be considered stable based on comparison with the data available in literature [M.-Christine and Cristina 2003].

A stable EC would surely be expected to associate with stable TDS readings as dissolved solids contribute towards electrical conductance. The TDS in the extract of the vermicasts, on average, was in the lower ranges. The ammonium content in the solid residue was below health standards, while nitrate and phosphate contents were also comparable to data found in literature [Hänninen *et al.* 2003; Manios and Stentiford 2004]. The lower temperatures encountered in the vermicomposting matrix were helpful to the nitrifying bacteria that converted the ammonium-N into nitrate-N.

The pathogen counts in the final vermicast were reported as less than 100 CFU per 100ml extractant of 100 gm vermicasts sampled from the lower chamber. This was excellent reduction given the very high pathogen content in the raw substrate based on data in the literature [Zucconi and de Bertoldi 1986; Farrell 1993]. The top chamber samples were not analysed due to expected higher counts due to introduction of liquid waste, which contains the high pathogen counts. It has been reported that worm treatment produces a 100-1000 fold reduction in levels of faecal

coliforms, cutting numbers of *Salmonellae* and other gut viruses and parasitic worm eggs [Fox 2001].

The pathogen reduction achieved in this test could be the result of the action by worms and other composting organisms as well as competition with indigenous microorganisms in the composting medium. This inference originated from the temperature profile that was followed during the vermicomposting process. The temperature in the vermicomposting mass never reached thermophilic ranges where pathogen destruction occurs in microbial composting. Fig 10.1 gives the temperature readings in the matrix for the entire testing period encompassing the 7 trial runs. Generally, it could be observed that the temperature varied in relation with the ambient temperature which was high during summer (Dec-Feb) and the warmer periods of autumn (Mar-May) and spring (Sept-Nov) season months while it was low during winter (Jun-Aug) and cooler months of autumn and spring seasons.

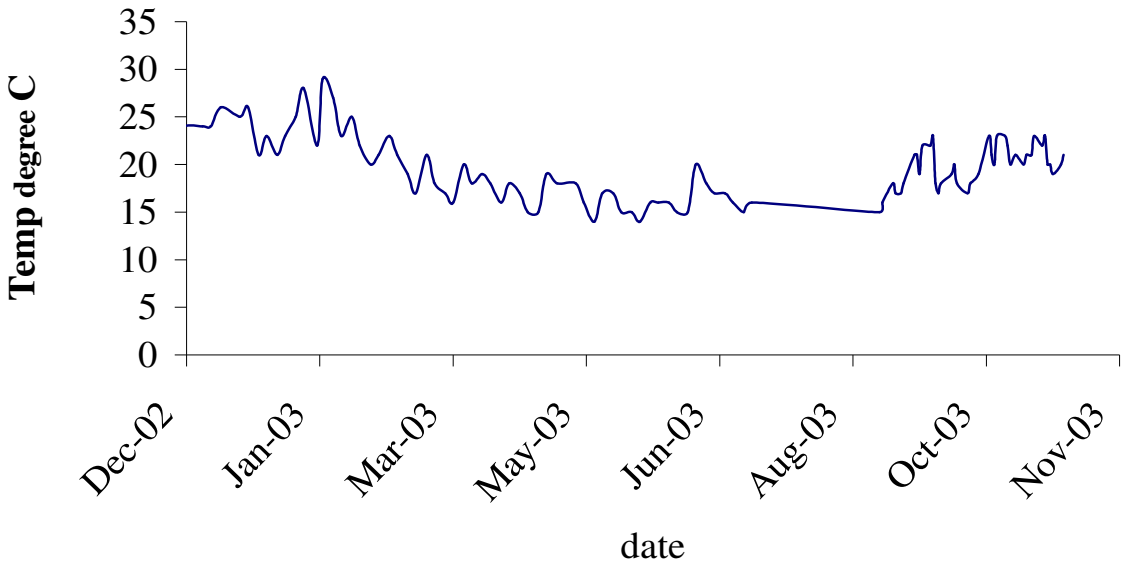

Figure 10.1 Temperature profile of solid matrix for the overall testing period

10.4 Conclusions

This chapter presented and analysed the solid waste material transformations in the prototype vermicomposting unit. Different parameters were identified and monitored for the different composting cycles. These parameters were pH, electrical conductivity, total dissolved solids, ammonium-N, nitrate-N, ortho-phosphate, faecal coliform, *E.*coli, mass reduction and volume reduction. It was found that all these parameters were in good agreement, in terms of variation trends, with the treatment received by the liquid waste that was filtered through the vermicomposting mass.

While the pH remained in the slightly acidic ranges, the electrical conductivity readings that averaged at 2.07 mS/cm for all the trial runs pointed to stable product. Total dissolved solids increased along with nitrate and phosphate readings. High nutrient values could be considered an advantage, considering the intended use of the solid residue of the process. Ammonia reductions were good, and the final product contained only small concentrations and open curing of the mature vermicasts could reduce these. Faecal coliform and *E. coli* were found to have reduced to safe levels. The level of pathogen reductions achieved for the liquid wastes (chapter 9) could be further affirmed by the pathogen reductions in the filtering medium. Further studies that could achieve better pathogen reduction of different organisms are recommended.

Mass and volume reductions achieved in the process were within the ranges found in literature. The final residue had an average weight of two-thirds of the raw waste material, calculated from the input data. The volume of the product, average of the

seven trial runs, was less than one-third of that of the input. Volume reduction being one of the ultimate aims of vermicomposting, the result is satisfactory. Further studies could confirm and optimise the mass reduction.

In the following chapter the results of the analysis of the performance of the system will be used in calibrating the empirical model of the system based on mass-balance and processes.

CHAPTER 11 A BUDGET MODEL BASED ON MASS BALANCE ANALYSIS

11.1 Introduction

There are many physical, chemical and biological reactions making up the processes of composting and vermicomposting and the interaction of these processes has proved a challenge in theoretical and empirical analysis of composting [Cabañas-Vargas *et al.* 2003]. Organic waste treatment has been the subject of several models based on the active phase of the process. But such attempts in composting, especially vermicomposting, are rarely found in literature possibly because vermicomposting is unlike the better known microbial composting, and has received less research interest. This chapter presents an analysis of vermicomposting in the context of a very simple budget model based on the results obtained from the tests conducted in this project, and is expected to give a basis for on-going tests on the system developed for the project.

It was realised early in the development of this thesis that it would be well outside of the scope of the thesis or the time available to develop a complete analytical description of the system. While a wealth of models is available to describe the processes operating in wastewater treatment plants and composting plants [Hamelers 1992; Alshawabkeh and Adrian 1997; Münch and Pollard 1997; D'Agata and Carne 2001; IMA-KTH 2001; Kenway *et al.* 2001; White *et al.* 2003; Zacharof and Butler 2004a] even these models are contentious, as the modelling is not considered by

some to be exact. Modelling vermicomposting systems is arguably more complicated because of the nature of the interaction of the solid, liquid and biological phases. The modelling approach adopted in this thesis is simplified and admittedly descriptive and empirical.

Several approaches could be adopted to develop models of the vermicomposting system. An ecological approach would emphasise energy gains and losses through the system. A mass-balance approach will provide predictive and design tools for the system. A kinematic approach would require a significant body of information on the reactions taking place within the system. For this thesis it was decided to utilise a mass-budget approach. Reasons for adopting this approach relate to the availability of data and the relative simplicity of the modelling.

11.2 Modelling In Biological Waste Treatment

Mathematical modelling of environmental systems undergoing biological transformations has focussed on anaerobic processes. The biochemical and hydrological processes in large anaerobic systems such as landfills have received considerable attention. Mathematical modelling of biological and chemical transformations in landfills have been the subject of extensive research, and has given considerable though inconclusive examples of various models focussing on landfill leachate [Onargan *et al.* 2003; Streese and Stegmann 2003; Visscher and Cleemput 2003; White *et al.* 2003; Zacharof and Butler 2004a, 2004b].

One study combined biochemical and hydrological models into an integrated representation of the landfill environment [Zacharof and Butler 2004a]. In the study,

waste decomposition was modelled using traditional biochemical waste decomposition pathways combined with a simplified methodology for representing the rate of decomposition. Due to the limitations in data collection from landfill sites, significant emphasis was placed on improving parameter identification and reducing parameter requirements. In another study, the same authors attempted a functional model on the waste degradation and transport systems within a landfill, integrating microbiological processes with hydrological processes. The model was based on a single complex organic molecule and analysed the process reactions in detail [Zacharof and Butler 2004b].

The concept of a generic numerical model that includes simulated transport of leachate and gases and the consolidation of solids in landfills was presented by White *et.al.* (2003). In their model, the four components of degrading waste, solids, biomass, leachate and gas, coexisted and were linked and interacted through the leachate phase. This model concentrated on the chemical reactions and biomass conversion. The study could assist in developing a model of the vermicomposting system, given the differences in process are taken into account [White *et al.* 2003]. Another similar model reported in literature focussed on methane production in landfills [Visscher and Cleemput 2003].

11.3 Modelling a vermicomposting system

Data on vermicomposting systems are scarce, and no reliable models exist that are useful in developing a vermicomposting system for domestic waste management. The available models on other biological waste treatment technologies can only be referred to for conceptual development [Payne 1970; Mitchell 1983; Jefferies and

Audsley 1988; Pollard and Greenfield 1997; Cabañas-Vargas et al. 2003]. An input-output model based on mass balance is attempted in the following sections based on data available from the different trial runs in the project discussed in this thesis. The parameters of interest are nitrogen, phosphorous, water, solid substrate (mass and volume), worm biomass and pathogen content. The parameters can be regrouped based on the form of material in which they are analysed:

- Solids: worms, raw solid waste, final compost
- Liquid: pathogens, ammonia-N, nitrate-N, phosphate-P

The process diagram for the basic composting process is given in Fig 11.1.

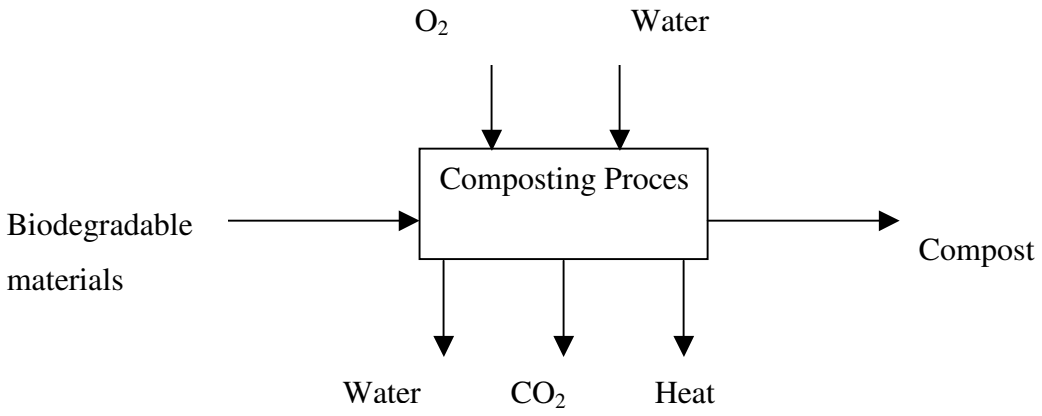

Figure 11.1. Process diagram of basic composting process

This diagram can be modified for a vermicomposting process based on the input-output balance of the above-mentioned parameters as in Fig 11.2. Heat dissipation is large and temperature build-up is avoided, but heat output is ignored.

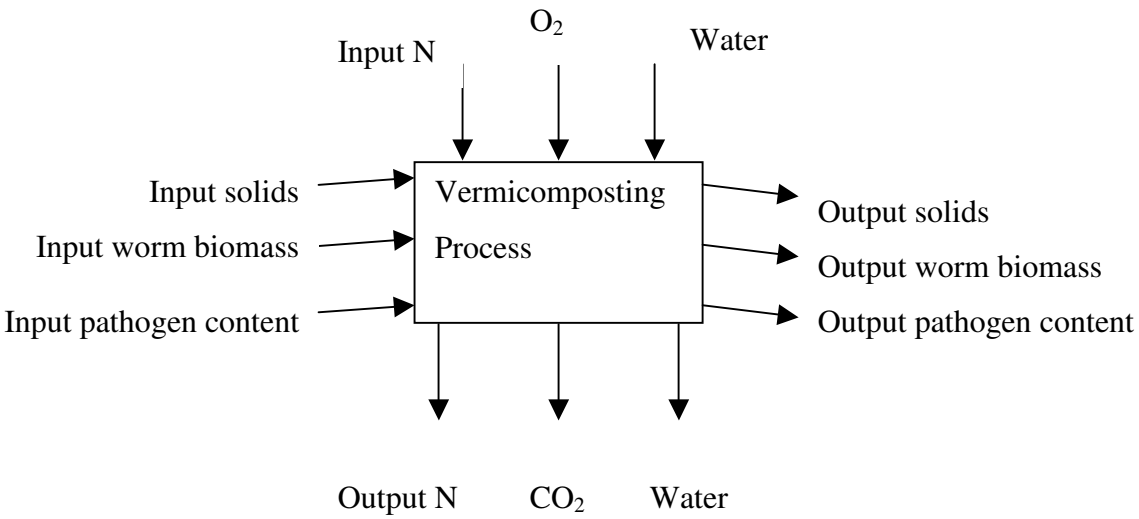

Figure 11.2. Process diagram of the process based on parameters of interest

The mass balance chart for worm biomass is given in Fig 11.3. A linear regression trendline is added to the chart to assist in predicting the trend of the mass variation. It can be seen that the increase in worm biomass has only been small in all the different trial runs. This means the process did not progress as predicted in literature, namely that the worm biomass will double in a composting cycle period, though data from waste treatment pointed to success of the action of the worms. A possible reason for this small increase in worm mass is the confined space and vertical structure of the unit.

The worm stocking rate is generally decided based on the surface area of the substrate matrix and the type of system and structure of the matrix is not accounted for. It may also be that the initial worm population was sufficient to process the inflowing waste and that the system could not support a larger population. In which

case, the worm mass would not increase but the compost output would balance the inflow of solid waste. Clearly there needs to be further studies on this issue of worm populations and their biomass changes during the reaction period.

11.3.1 Mass-balance models

The above discussion on worm biomass sets the pattern in this chapter for simple models utilising the data of the test trials presented in the previous chapters.

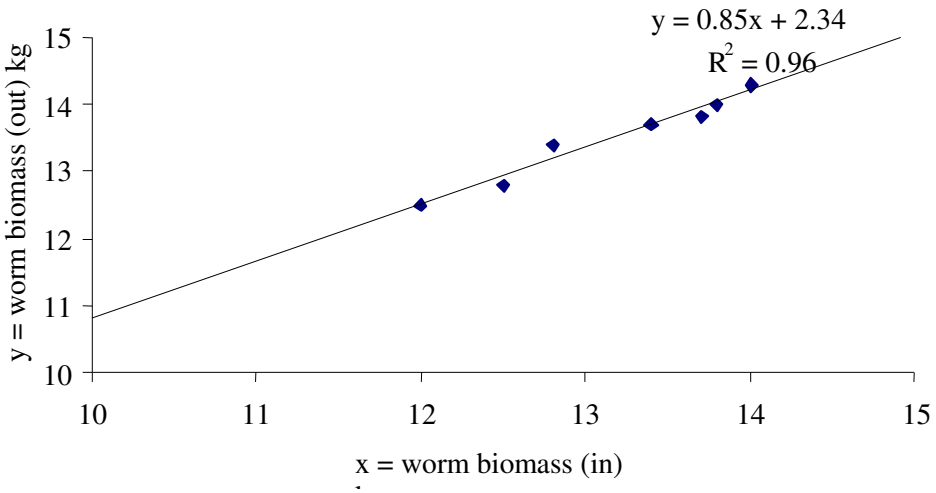

Figure 11.3 Input-output mass balance of worm biomass with linear trendline

Here, a simple regression model is represented as:

$$\text{Worm biomass}_{OUT} = 0.85\ (\text{worm biomass}_{IN}) + 2.34 \qquad \ldots 11.1$$

Coefficient of determination of the trendline is 0.96 and coefficient of correlation is 0.98. The data from the tests doesn't show good worm biomass gain, but the high coefficient of determination explained points to reliable model. The model in equation 11.1 applies only for variation of worm biomass, not as a complete model. For example, equation 11.1 yields a wormbiomass_{OUT} of 2.34 while

wormbiomass$_{IN}$ equals zero. Further tests and data analysis into such models is necessary to validate the tested regression model.

The term 'solid waste' in this chapter means the total solids as calculated as the sum of raw input solid waste and the TSS component of blackwater and is given in chart Fig 11.4 against the final vermicasts.

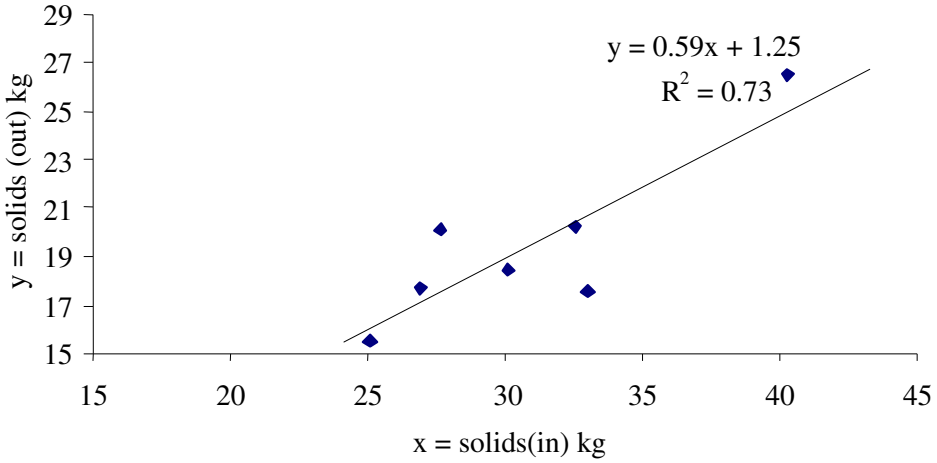

Figure 11.4 Input-output mass balance of solids treated in the unit with linear trendline

Here, $\text{Solids}_{OUT} = 0.59\ (\text{solids}_{IN}) + 1.25$ …11.2

The coefficient of determination is 0.73 and correlation coefficient is 0.86. The models suggests that 50% of the solid waste mass is reduced although there appears to be a threshold for this waste reduction. Applicability of the equation 11.2 is limited to variation in the solid content during operation and more analysis is necessary to generalise the model for the limits of applicability.

Similarly, Fig 11.5 shows the relation between the total weight of the solids and worms together before and after the treatment received in the vermicomposting unit. The total weight of solids includes the residual waste, the compost and the solids in the water flowing into or out of the system. This relation assumes the total initial and final mass within the unit and includes the worm biomass as the worms are grown and dead worms are degraded. No account is made for moisture or gas losses. Worms grow by absorbing food from the solid waste material and the mass of dead worms are degraded and added into the final castings.

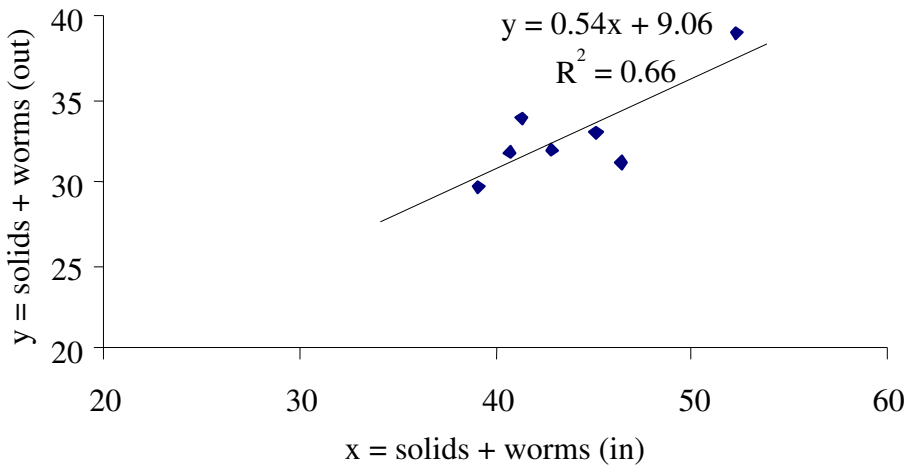

Figure 11.5 Input-output chart of total solid mass in the vermicomposting unit with linear trendline

The simple regression model:

$$\text{Solids + worms}_{OUT} = 0.54\ (\text{solids + worms}_{IN}) + 9.06 \qquad \ldots 11.3$$

has a coefficient of determination of 0.66. Though the worm biomass gain was low there is clearly a significant reduction of the solid waste added to the system.

Carbon and nitrogen cycles involve reactions in different states such as solid to solid, solid to liquid, liquid to liquid, liquid to gas etc as well as to and from the biomass of worms. Analysis of nitrogen lost in the gaseous form was not included in the project's monitoring regime, therefore complete picture of the N-cycle is not available. Moreover, the input food waste was not analysed for its C: N ratio and individual C and N values. Inability to assess the Total Organic Carbon (TOC) in the samples also causes inadequate data.

Fig 11.6 gives the N-cycle for the available data from the analysis of liquid samples. This relationship presents the hydrological N-cycle with regards to the vermicomposting unit prototype. The unreliable model points to inadequate data for analysis as well as to the possibility that some N from the solids (that was not included in the tests) was also lost through effluent, which should be recaptured through further treatment.

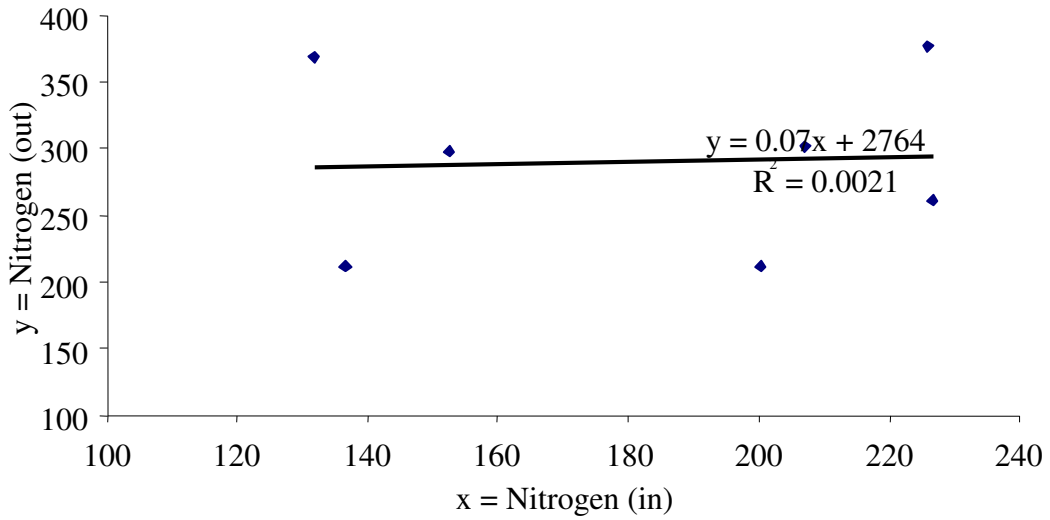

Figure 11.6 Input-output nitrogen cycle of liquid waste stream

It should be noted from Figure 11.6 that the indications are that widely varying inflows of N do not lead to large variations in the outflow of N in the water. The results suggest a robust processing system that is capable of responding to different N loads, especially when it is realised that the N load of the organic solid input into the processing system is not included. The relationship also suggests that there are either considerable losses of N via the atmosphere (gas) or that the N composition of the compost is higher than that of the solid input. The simple regression model for N-cycle is not reliable due to the very low R^2 value.

The input-output relationship of pathogen content, given by faecal coliform counts, is given in Fig 11.7. Here, the total numbers of faecal coliforms are measured from the average input and output figures of 4L and 3L (average) respectively for raw influent and secondary effluent. This gives a crude measure of the total pathogen input and output.

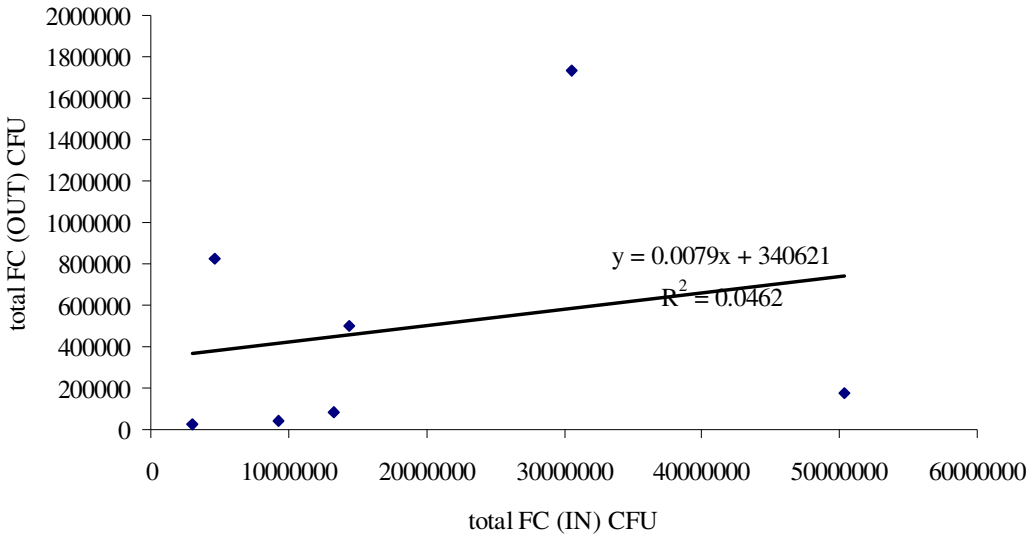

Figure 11.7 Faecal coliform input-output relationship

Here, the model can be represented as:

$$\text{Faecal coliform}_{OUT} = 0.0097 * \text{faecal coliform}_{IN} + 340621 \quad \ldots 11.5$$

With a coefficient of determination of 0.0462 the relationship is not significant. This doesn't give a reliable model, though the actual reduction in CFU/100ml discussed in chapter 9 shows the process achieving good results in terms of pathogen reduction. The relationship does suggest however that there is a significant reduction in the pathogen content despite there being no significant relationship in the inputs and outputs. As with the earlier models, limit of applicability is affected by limited data available and only through further study can this be developed into a generalised model.

A poor relationship can be observed for the input-output relationship of *E. coli* (Fig 11.8). Not too much can be read into these simple models of pathogen indicators, as the tests are really indicator tests and not reliable estimates of the total numbers of pathogens treated in the system.

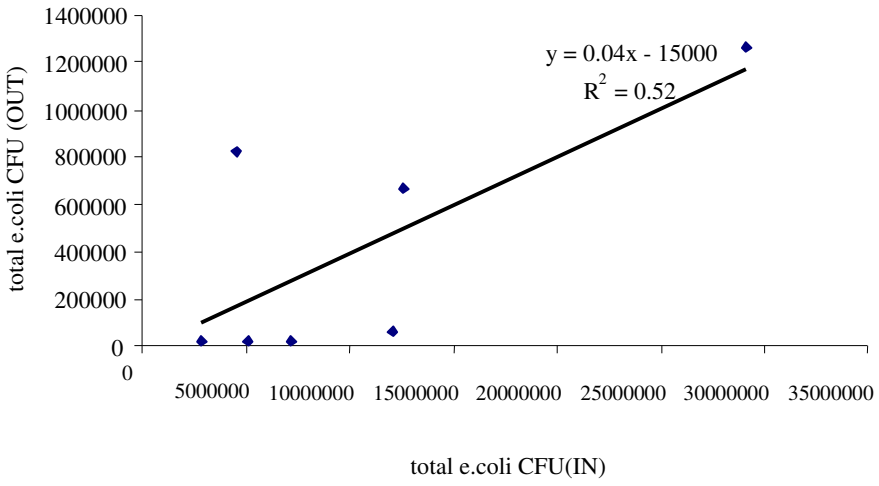

Figure 11.8 *E.coli* input-output relationship

The empirical equation available from the presented data does not give a reliable model, though the actual reduction in numbers of CFU points to the fact that the process of vermicomposting achieving pathogen reduction. More detailed studies and analysis are necessary with regards to faecal coliform and *E.coli*.

11.3.2 Developing an empirical model for the vermicomposting unit

The parameters that are controlled directly by the operator, such as the input of the materials within the unit can be of importance in modelling the system. These parameters generally include mass of solid waste materials, mass of water, biomass of live worms and C: N ratio. Measurement of the latter two parameters in the solid waste input was difficult during the testing period due to unavailability of test instruments for TKN and TOC. This section attempts to generate simple models based on a mass-balance of some of these parameters.

The material transformation from waste materials to worm biomass gain is mostly by conversion of organic C and N. Considering the mass gain through new generation of worms and mass lost through dead worms, the following relationship can be formulated:

$$\text{Worm mass}_{OUT} = f(\text{Worm mass}_{IN}) \quad \ldots 11.6$$

This functional model will not explain the resulting mass gain or loss in worm biomass due to the other factors affecting the worm population growth, such as the quality and quantity of food waste that is available to the resident worms, atmospheric conditions such as temperature and ambient humidity, weather patterns

etc. This is evident from the departure of the results seen in chart 11.3 and empirical equation 11.1 from the expected doubling of worm biomass.

Similarly, an empirical equation can be formulated for the solid waste matrix:

$$Solids_{OUT} = f\ (Solids_{IN}) \qquad \ldots 11.7$$

An empirical equation for mass of water recycled in the system:

$$Water_{OUT} = f\ (Water_{IN}) \qquad \ldots 11.8$$

Taking into account the water lost by evaporation,

$$Water_{OUT} = f^1\ (Water_{IN})_{moisture} + f^2\ (Water_{IN})_{effluent} \qquad \ldots 11.9$$

For Nitrogen,

$$N_{OUT} = f\ (N_{IN}) \qquad \ldots 11.10$$

This N is partly lost in gaseous form, partly appears as worm biomass, as part of the castings and in the effluent.

$$N_{OUT} = f^1\ (N_{IN})_{worm} + f^2\ (N_{IN})_{casting} + f^3\ (N_{IN})_{effluent} + f^4\ (N_{IN})_{gas} \qquad \ldots 11.11$$

And Carbon,

$$C_{OUT} = f\ (C_{IN}) \qquad \ldots 11.12$$

C also appears in different forms as:

$$f\ C_{OUT} = f^1\ (C_{IN})_{worm} + f^2\ (C_{IN})_{casting} + f^3\ (C_{IN})_{gas} \qquad \ldots 11.13$$

$$= f\ (C_{IN})$$

Carbon lost in effluent is considered negligible.

Composting and vermicomposting are very complex processes involving physical, chemical and biological transformations of materials in solid, liquid and gaseous forms and different organisms. This fact and the lack of previous attempts make it difficult to explain the processes based on the above empirical models. Different

factors affect the material transformation and biological growth within the composting system and these factors are inter-related. Therefore, models based on individual parameters do not offer the complete picture, but models incorporating different parameters will. Developing them into more functional models using the data will provide an edge in the process of finalising a complex and complete model.

These simple models can be combined to develop more complex models for analysing the vermicomposting unit in terms of mass balance of the input and output materials, based on the parameter that is of importance. For example, regarding the worm biomass increase, the most relevant quantifiable parameters are the input worm biomass and solid waste input C: N ratio.

$$\text{Worm mass}_{GAIN} = \alpha^* \text{ Worm mass}_{OUT} + \nu^* N_{OUT} + \kappa * C_{OUT} - \beta * \text{Worm mass}_{IN} + c_1 \quad \ldots 11.14$$

Where α, β, κ and ν are all empirical/functional constants for the respective parameter and c_1 is the equation intercept.

In analysing the water cycle, the water lost through evaporation and biological needs of worms and other organisms also need to be taken into account. This depends on many factors such as the ambient temperature within the unit, the external atmospheric temperature, worm activity – high or low (which determines the air channels within the solid matrix but is not usually quantifiable), the water added as moisture content in the solid input etc. This can be used in modifying the equation 11.9.

Similarly, the solids reduction in terms of mass of the material converted can be represented as a complex model incorporating all the different elemental masses and solids component of the liquid waste (TSS and TDS) and losses through gaseous and liquid form.

$$\begin{aligned} \text{Mass}_{\text{REDUCTION}} = {} & A^{*}\ \text{Solids}_{\text{IN}} + B^{*}\ \text{Solids}_{\text{INFLUENT}} + C^{*}\ \text{Worm mass}_{\text{IN}} + D^{*} \\ & \text{Water}_{\text{IN}} + E^{*}\ \text{N}_{\text{IN}} + F^{*}\ \text{C}_{\text{IN}} - \\ & \{G^{*}\ \text{Solids}_{\text{OUT}} + H^{*}\ \text{Worms}_{\text{OUT}} + I^{*}\ (\text{N}_{\text{OUT}})_{\text{gas}} + J^{*} \\ & (\text{N}_{\text{OUT}})_{\text{effluent}} + K^{*}\ (\text{N}_{\text{OUT}})_{\text{castings}} + L^{*}\ (\text{C}_{\text{OUT}})_{\text{castings}} + M^{*} \\ & (\text{C}_{\text{OUT}})_{\text{gas}} + N^{*}\ \text{Water}_{\text{OUT}}\} \\ & + c_2 \qquad \ldots 11.15 \end{aligned}$$

Where *A, B, C, D, E, F, G, H, I, J, K, L, M,* and *N* are empirical functional constants for the respective parameters. On closer analysis of equations 11.14 and 11.15, it can be assumed that the empirical constants for relevant parameters in both models are the same. That is: $\alpha = H$ and $\beta = C$.

11.4 Conclusion

This chapter attempts the development of empirical models for explaining the process of vermicomposting in terms of the working prototype developed for treatment of domestic blackwater and solid waste. Simple regression models based on the data from the seven trial runs of the system, discussed in chapter 9 and 10, are presented followed by discussions on empirical models on the different aspects of the processes taking place within the system.

The regression models present the process to be predictable thus making the models reliable, for certain parameters while for others more data is necessary. Overall, the

models and data present the process to be successful in reducing pollution and pathogen numbers through the process, but modelling the system will be complex. Physical characteristics of the raw input solid waste as well as liquid waste are reliably represented in the models, such as solid reduction in the wastewater stream and mass reduction of the solid matrix, whereas models presented are not representative of the inference regarding treatment in terms of chemical pollutants such as nitrogen and microbiological agents including indicator organisms.

Empirical models developed for the system in this chapter are not conclusive due to lack of data for many parameters that were not analysed during the testing of the system. More studies and data analysis will surely contribute towards the development of complex models that will explain and predict the performance of the vermicomposting system. However, the attempt made in this chapter will show that it is possible to develop such models for vermicomposting systems treating mixed waste stream and points to the need for further research in this field.

CHAPTER 12 CONCLUSIONS AND RECOMMENDATIONS

In this thesis, an economic and user-friendly 'whole-of-waste management system' is presented for residential areas, particularly suitable for developing countries. The system treats treated domestic blackwater along with solid waste including garden waste, kitchen waste and other biologically degradable waste using vermicomposting technology. The 'bottom line' of the study is that the system works and is clearly a viable means of managing waste in domestic situations, with minimal costs to the user.

It was argued in the first chapter, that the different streams of wastewater originating at a normal household could be treated on-site along with solid waste. A detailed definition of composting was quoted from literature that gave an in-depth idea of the process. It was argued that a vermicomposting system would be most efficient in safely treating wastes on-site.

Due to a lack of scientific knowledge on vermicomposting, reactions occurring in a composting system are used to assist in understanding the transformation of waste by vermicomposting. Microbiological processes play an important role in the efficient functioning of the vermicomposting system.

The species of worms used in vermicomposting are important. The physical and biological parameters such as types of worms, Hydraulic Retention Time, Solid

Retention Time, aeration, method of composting, substrate composition and moisture content all are important in the design of a vermicomposting system.

A qualitative risk evaluation was conducted on the different aspects of domestic waste management and in vermicomposting. An extensive list of hazards associated with the on-site treatment of domestic waste including blackwater was prepared, followed by risk analysis and development of risk management techniques. A comparative risk study using different risk evaluation techniques – NSCA risk score calculator and risk evaluation matrix - with treatment options for blackwater of direct reuse in farming and septic tanks showed that vermicomposting has a lower level of risk. It was shown that by observing basic personal safety standards, and by conducting proper maintenance of the vermicomposting system, most risk could be averted/reduced to acceptable levels with the vermicomposting unit – both at the experimental level and in a real-world installation.

Initial vermiculture tests were conducted to evaluate data available from literature. It was ascertained that a worm stocking rate of approximately 12 kg/m^2 by biomass was adequate to sustain a healthy worm population. An initial phase of the vermiculture tests had failed, the reasons for which were evaluated with a second phase. It was found that vermicomposting could progress if favourable conditions were provided and most minor aberrations were self-correcting such as effects of atmospheric temperature fluctuations and changes in pH in the input material. Moisture was found to be a very important parameter for worms, as it decides the internal temperature and biological activity, such as appearance of fungi at low moisture levels. Worms would mass-migrate from bedding that lacks a suitable

moisture level of 60% minimum. A self-sustaining composting-worm population was developed during this experiment.

A working prototype of the vermicomposting unit for a single-person equivalent waste generation was designed. The prototype was constructed out of stainless steel that would withstand corrosion from the liquids within and leaching from the composting matrix. The design is scalable for a single household; a small community or an apartment complex resulted in the form of a compact vertical vermicomposting unit. The system could also be useful in areas such as farmhouses and remote dwellings as a means of total waste management.

The prototype was tested over a time period of 11 months. Variations in physical parameters (TSS, turbidity, TDS and conductivity), chemical parameters (pH, DO, BOD_5, COD, ammonium-N, nitrate-N and phosphate) and microbiological parameters (faecal coliform, *E. coli*) were examined. An average reduction of more than 90% was observed in TSS, while average 89% reduction in turbidity, 89% reduction in ammonia, 98% reduction in BOD_5, 70% reduction in COD and approximately 2 order of magnitudes of reduction in faecal coliform and *E. coli* CFU were reported. Average of 81% increase in DO showed good treatment received by the liquid. An increase in nitrate and phosphate content in the treated effluent caused a very high increase in conductivity, which would have to be dealt with in further studies. Generally, it was concluded that the treatment of the blackwater in the prototype vermicomposting unit was excellent.

The most important objectives of composting – mass and volume reductions - achieved in the prototype were within the ranges found in literature. The final residue had an average weight of two-thirds of the raw waste material with average reduction of 37%, calculated from the input data. The volume of the product, average of the seven trial runs, was less than one-third of that of the input, with a reduction of 71%.

An attempt was made to develop simple regression models for the vermicomposting unit. Such attempts have not been reported in the literature cited. The models developed in this chapter were not conclusive, probably due to lack of data, and the number of parameters required for the development of the complete and complex models that could explain the system. Directions for future studies to model the system were presented.

Recommendations

The studies in this research project showed that is it possible to treat blackwater at source using a simple and low-cost vermicomposting technology. The final acceptability and use of the technology should be enhanced using further studies:

- A full-scale study in an actual situation, preferably at a typical household in a developing country is recommended.
- More parameters such as heavy metals (Cd, Pb, Cr, Mn, Zn, Al, Ni etc), total organic carbon, accurate measurement of C: N ratio in the ingoing waste materials as well as final castings need to be studied in order to better understand the processes and model them.

- More detailed study of the pathogen content in the waste streams (liquid and solid) and in the treated effluent and castings is needed for a better understanding of the public health impacts.
- Development of a semi-automatic operational system along with solar power source should also be a study area.

It is concluded that a low-cost total waste management system that has low public risks and several benefits is viable. Vermicomposting proved to be appropriate for this system.

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GLOSSARY

Aerobic waste treatment – Treatment of waste and wastewater in presence of air.

Anaerobic waste treatment – Treatment of waste and wastewater in the absence of air.

Blackwater – Effluents from a flush toilet

C: N ratio – Ratio of carbon and nitrogen, based on mass balance.

C-cycle – Carbon cycle refers to the conversion of elemental carbon through different compounds and chemical reactions.

Composting – A process of converting organic waste materials into humus by controlled action of microorganisms. The process goes through different temperature ranges such as mesophilic to thermophilic and back to mesophilic, during which most of the pathogens and seeds are eliminated from germination or spread.

Composting worms – Certain types of earthworms are litter dwelling while others are soil dwelling. Members of the former type are faster in reproduction and in converting waste materials into a humus-like material called castings.

Greywater – All household wastewater excluding blackwater – includes kitchen sink effluents, laundry and bath wastewater.

Hydraulic Retention Time – Duration for which liquids are held in the treatment unit.

Integrated Solid Waste Management – A hierarchy of processes used in the management of solid waste materials that gives priority to different sustainable waste management options such as composting and recycling.

N-cycle – Nitrogen cycle refers to the conversion of elemental nitrogen through different compounds and chemical reactions.

Risk Calculator – A scaled nomograph for calculating the level of risk in quantitative or qualitative terms from the probability of each hazard and exposure level to the affected population and environment.

Solids Retention Time – Duration for which solid materials are held in the treatment unit.

Vermicasts – Excreta of earthworms including composting worms- a complete safe material for application as a soil enrichment material. This material contains valuable plant nutrients and soil microbes.

Vermicomposting – The process of converting organic waste materials into humus by action of composting worms such as red worms, red wigglers and tiger worms. Other insects such as mites, millipedes and beetles will also appear during the process.

Worm stocking rate – The rate at which composting worms are loaded into the treatment unit per unit surface area.

APPENDICES

Appendix 1 – Design drawings

Appendix 2 – Photographs of the prototype vermicomposting unit

Appendix 3 – Test methods employed

Appendix 4 – Photographs of analysis instruments used

Appendix 5 – C: N values of commonly composted materials

Appendix 6 – Collection and preservation of samples

Appendix 7 – A list of papers published

APPENDIX I DESIGN DRAWINGS

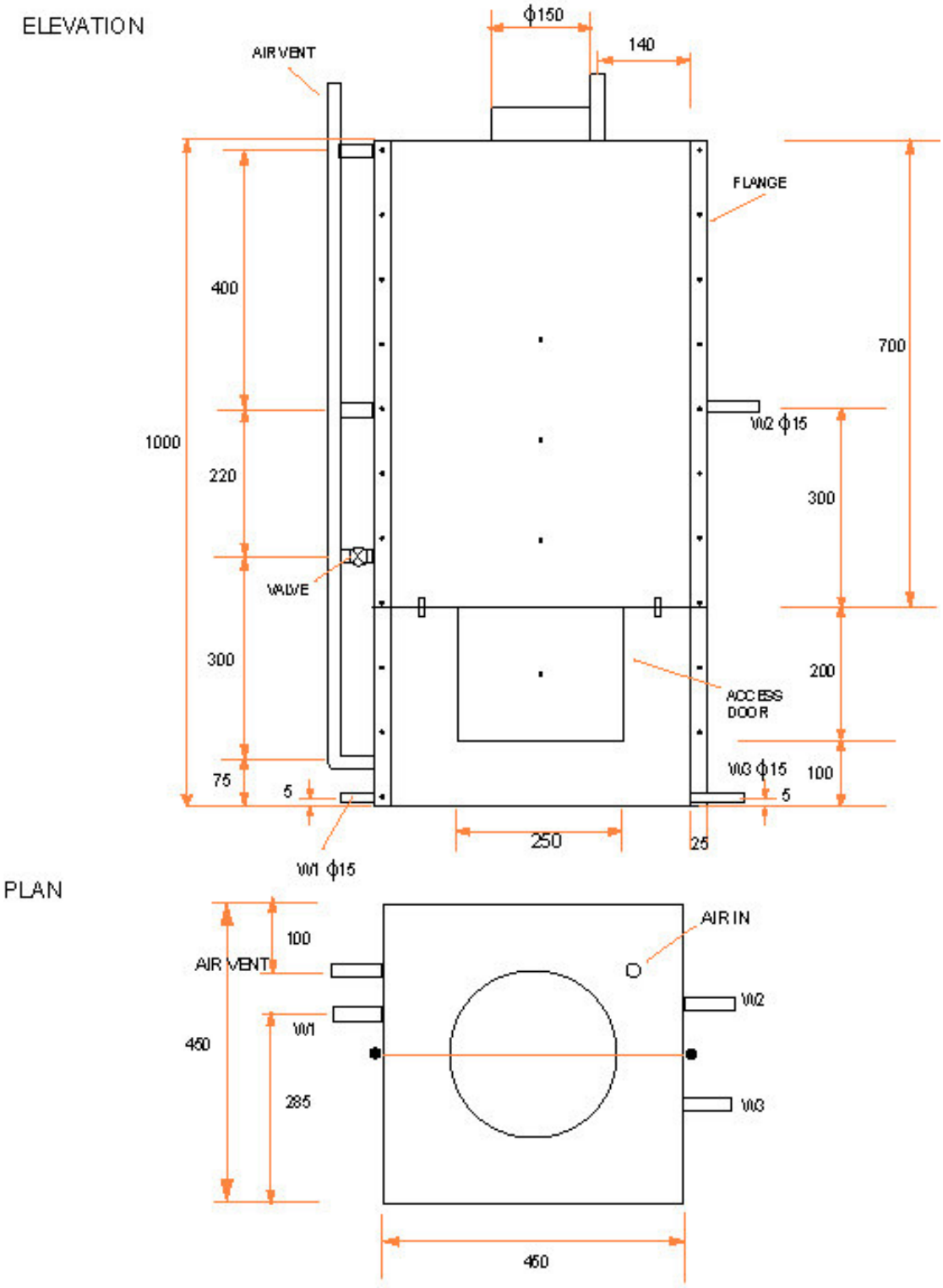

Fig. I.1A Elevation and plan of the prototype

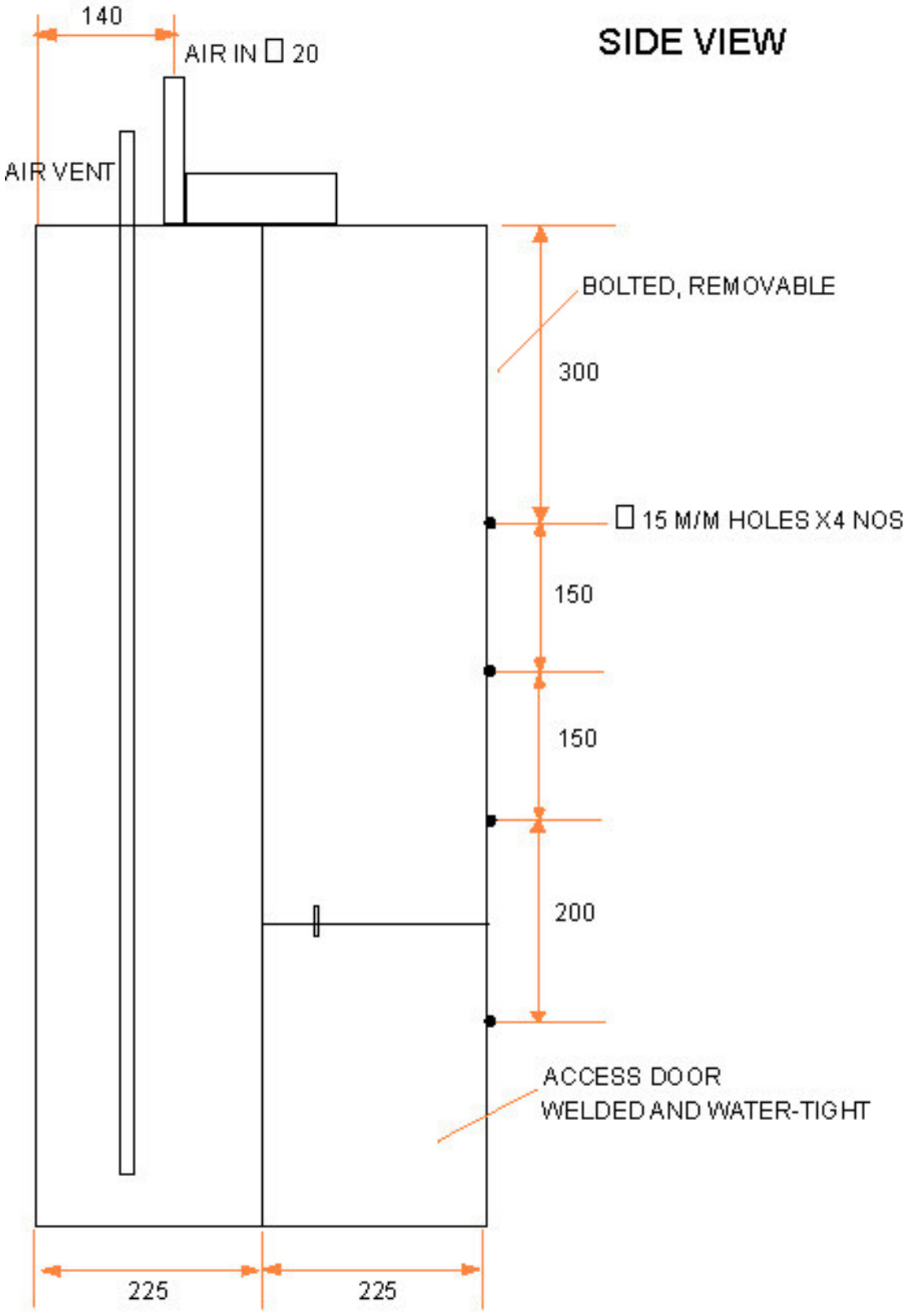

Fig I.1B Side view of the prototype

SECTION - FRONT VIEW

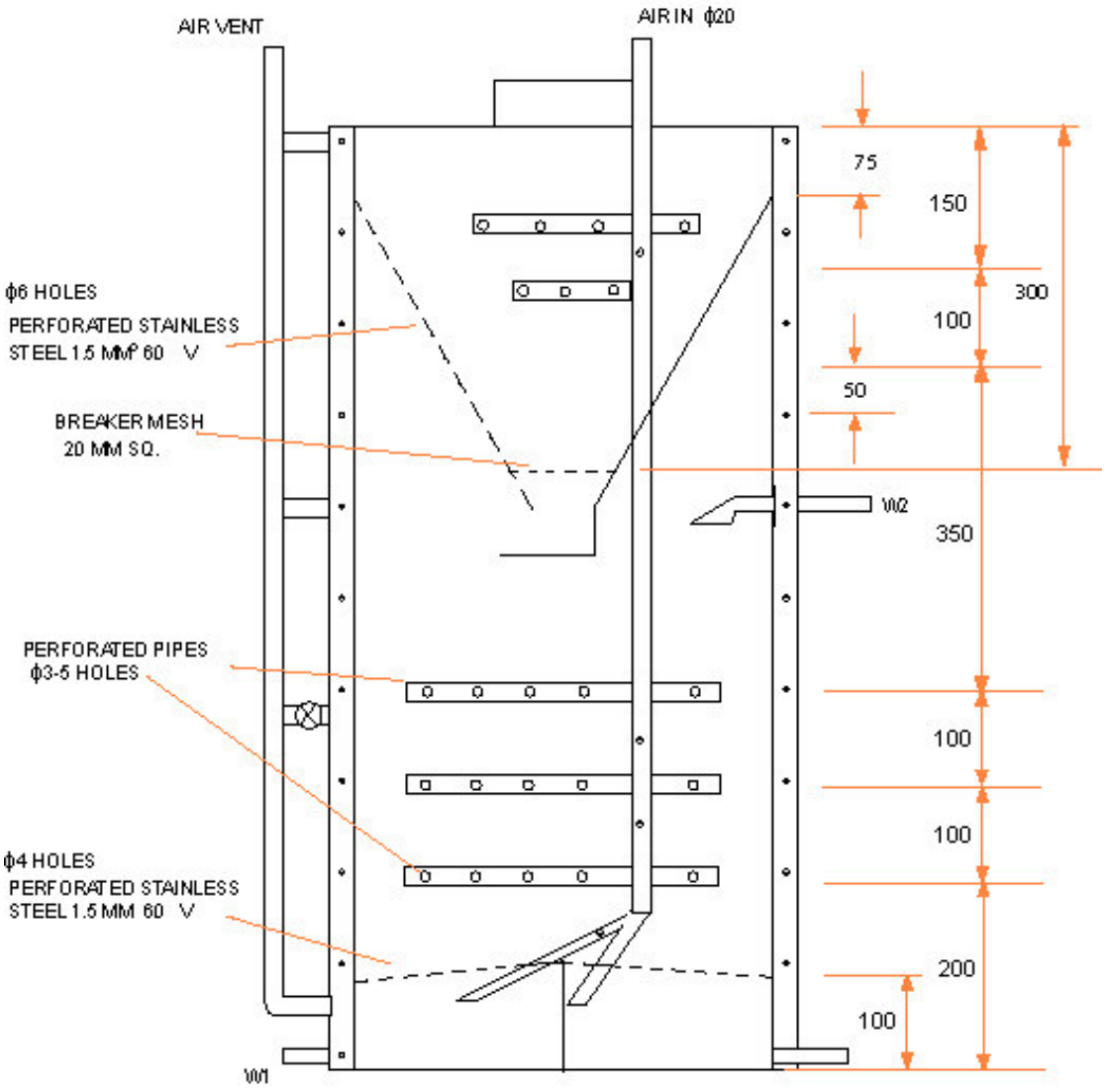

Fig I.2 Fromt view of the section of the prototype

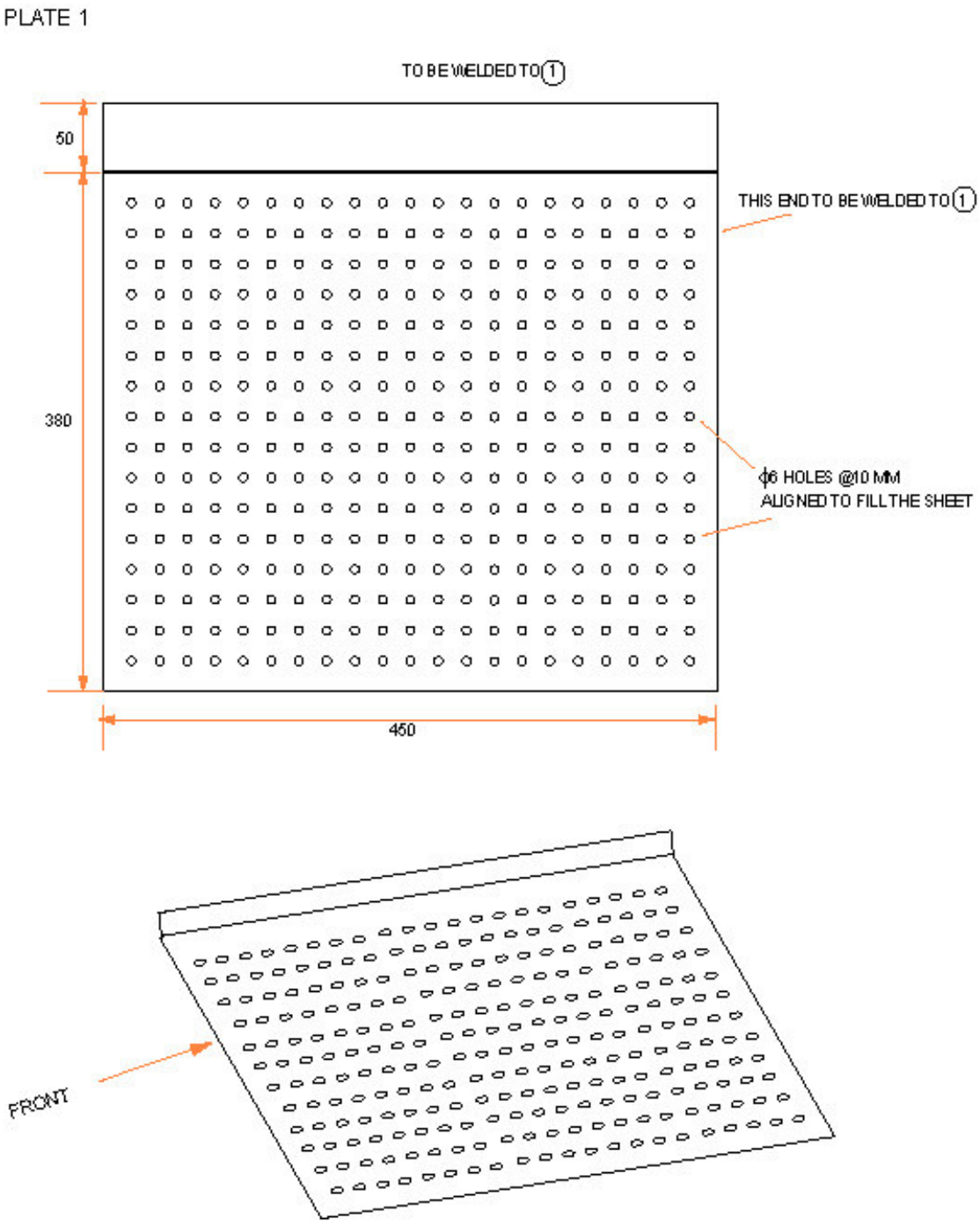

Fig I.3 Perforated side of the V-hopper chamber

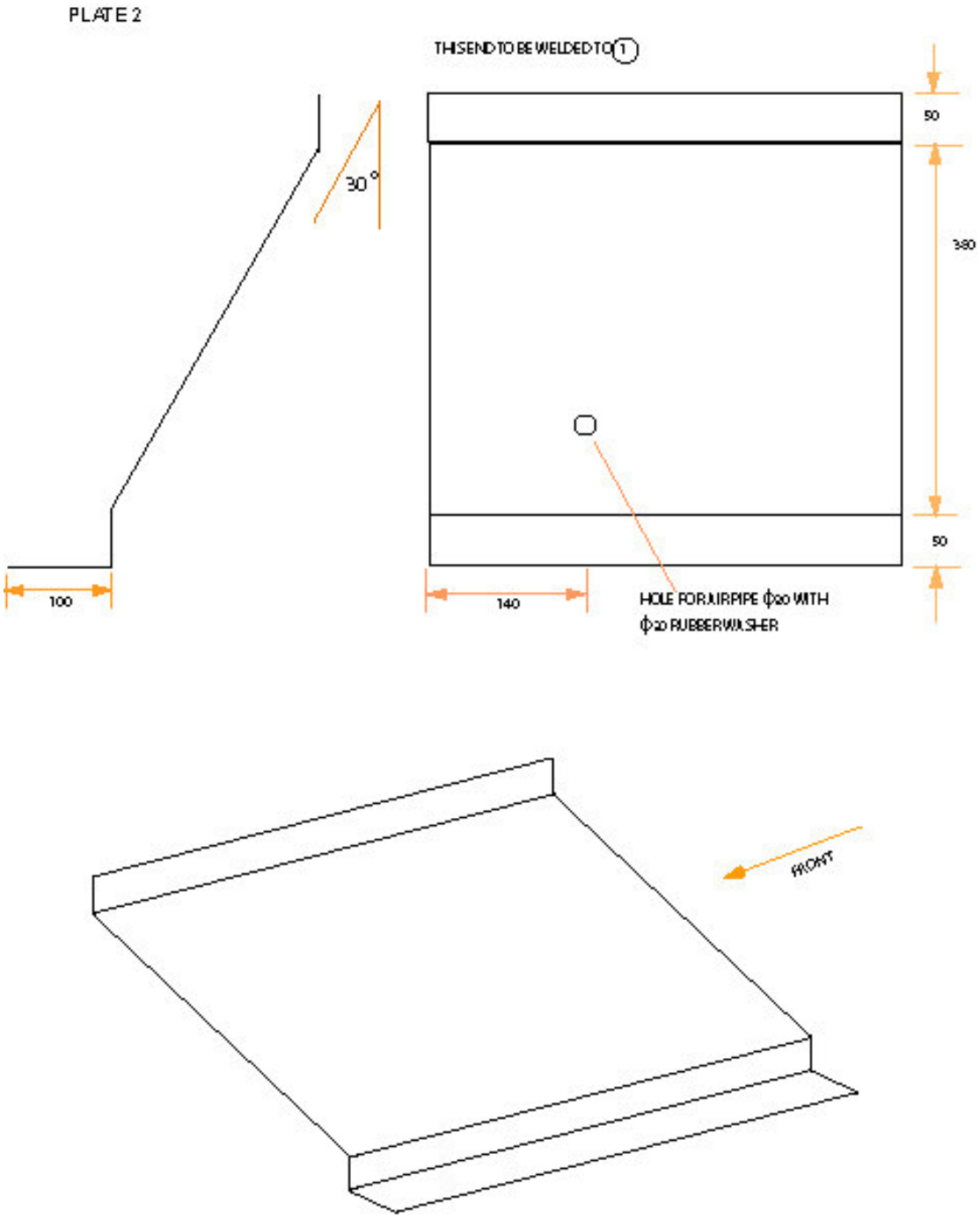

Fig I.4 Side 2 of the V-hopper chamber

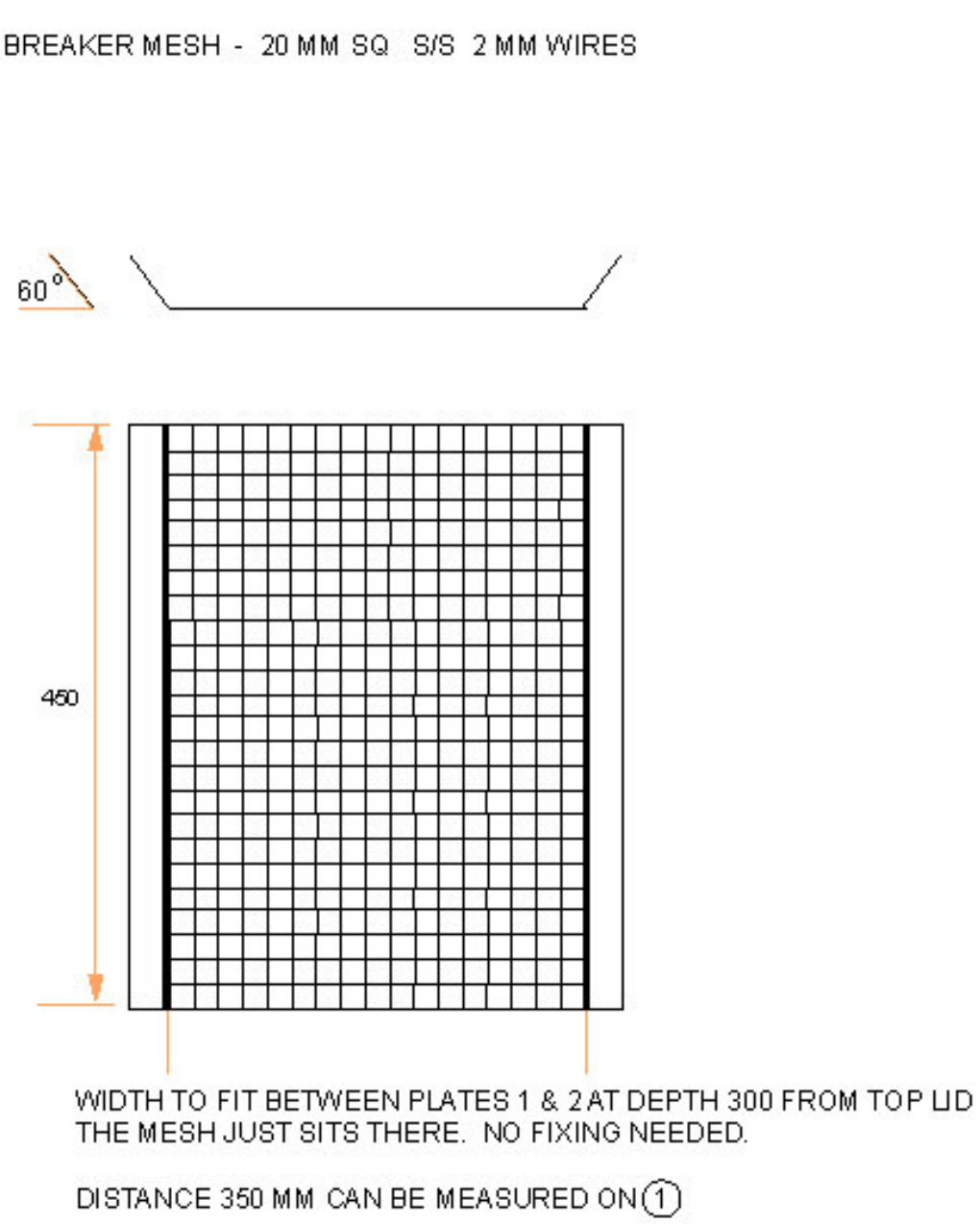

Fig I.5 Breaker mesh bar at the bottom of the V-hopper

FILTER PLATE TO SIT INSIDE THE BOTTOM-TRAY

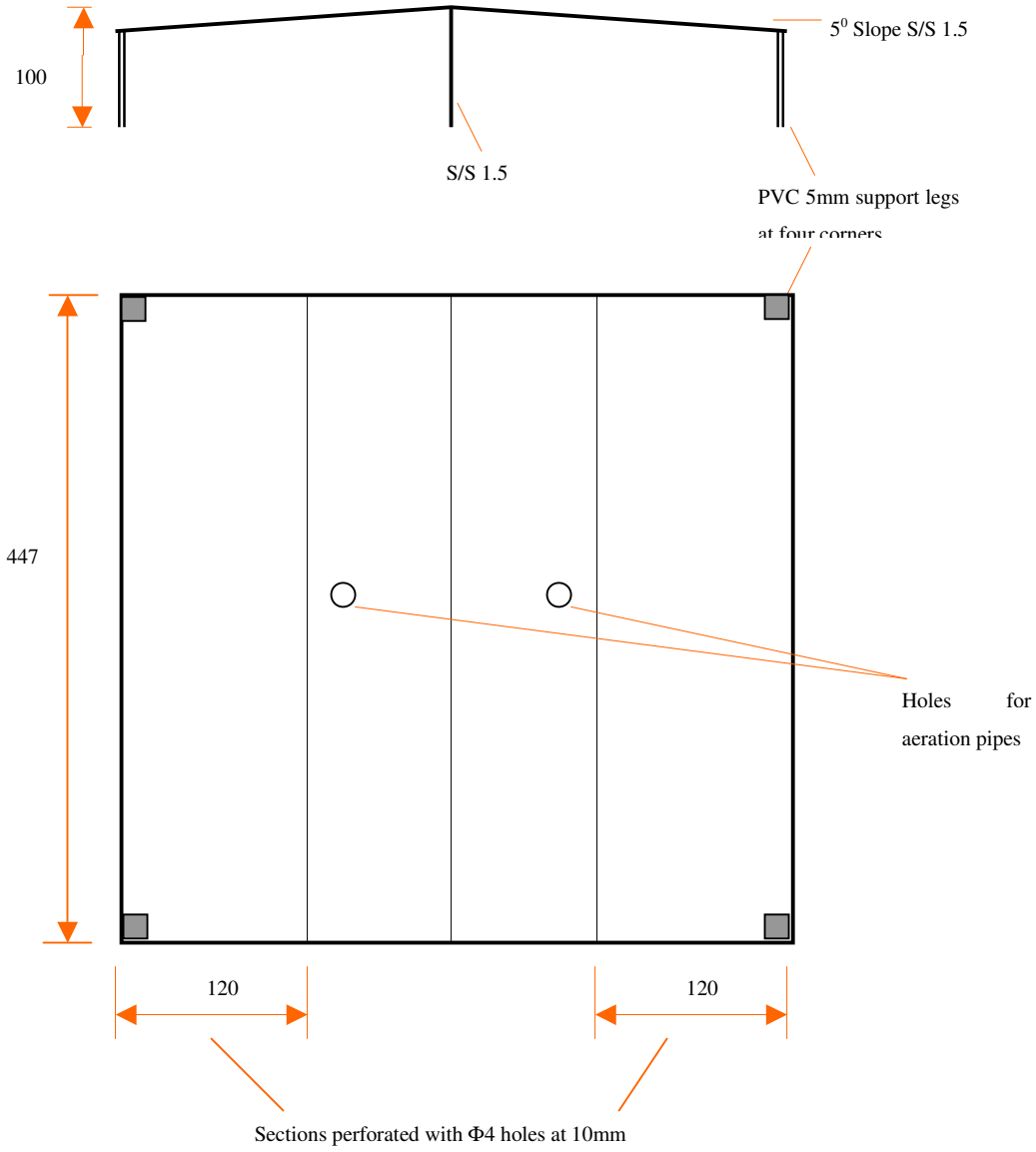

Fig I.6 Bottom plate of the lower chamber where the compost matrix is housed

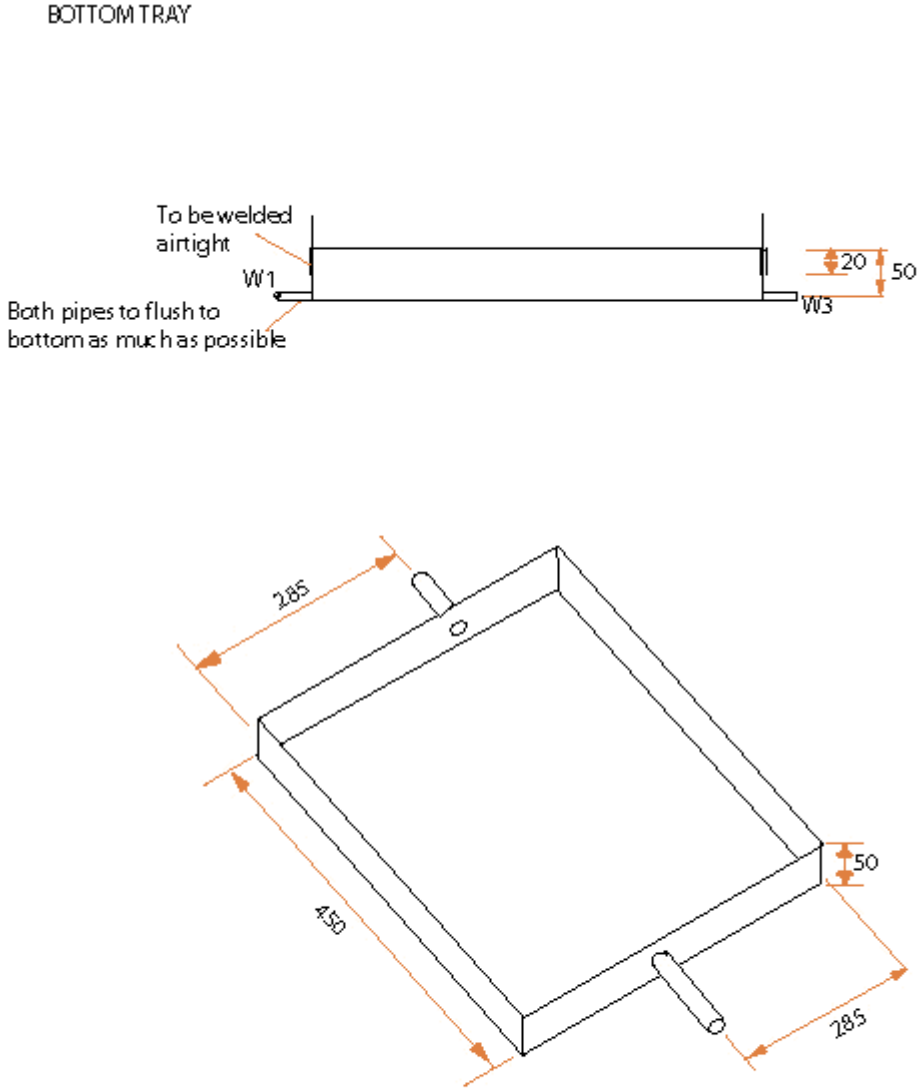

Fig I.7 Water holding tank (lower bottom chamber) of the prototype

TOP LID

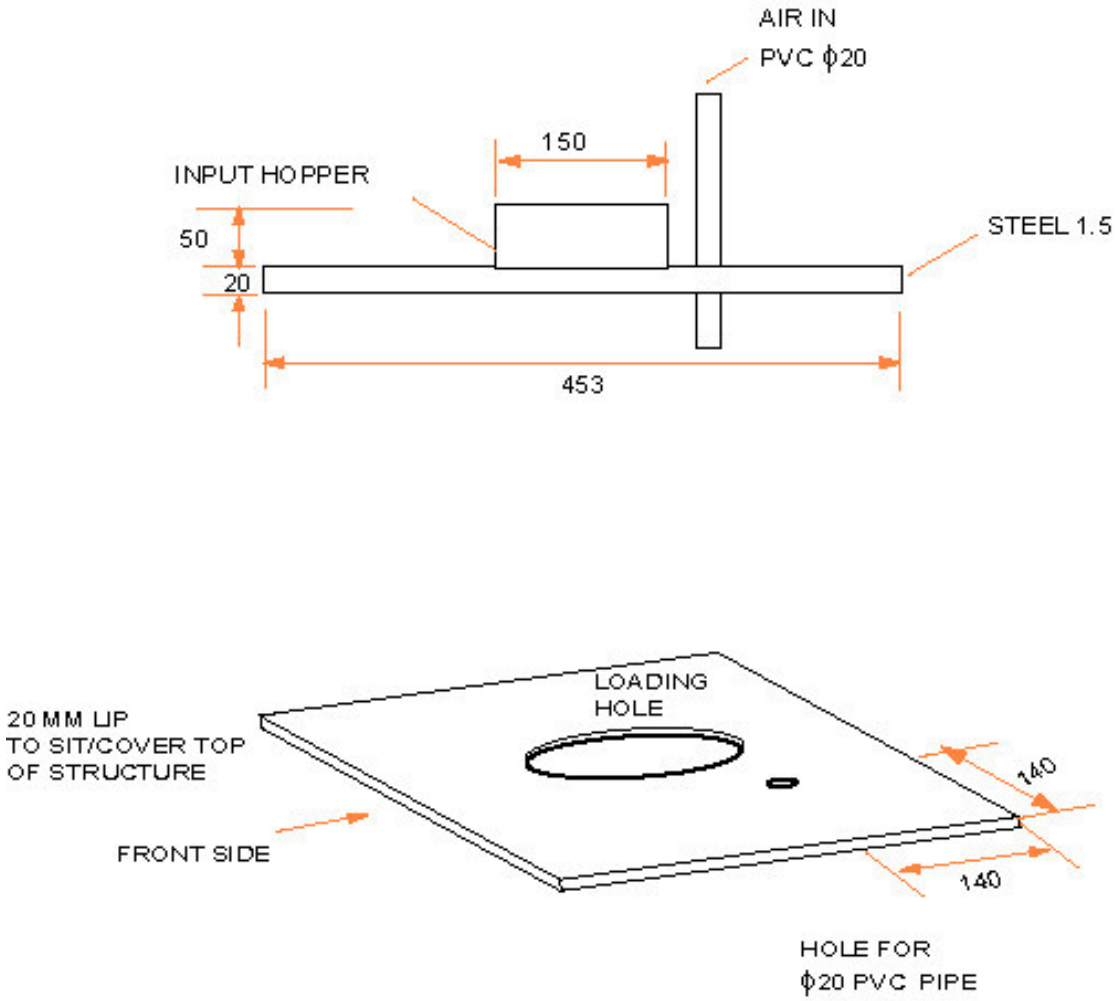

Fig I.8 The top-lid of the prototype unit

APPENDIX II PHOTOGRAPHS OF THE PROTOTYPE VERMICOMPOSTING UNIT

Fig II.1 The overall set-up of the prototype and the blackwater holding tank

Fig II.2 Addition of blackwater from the tank to the system

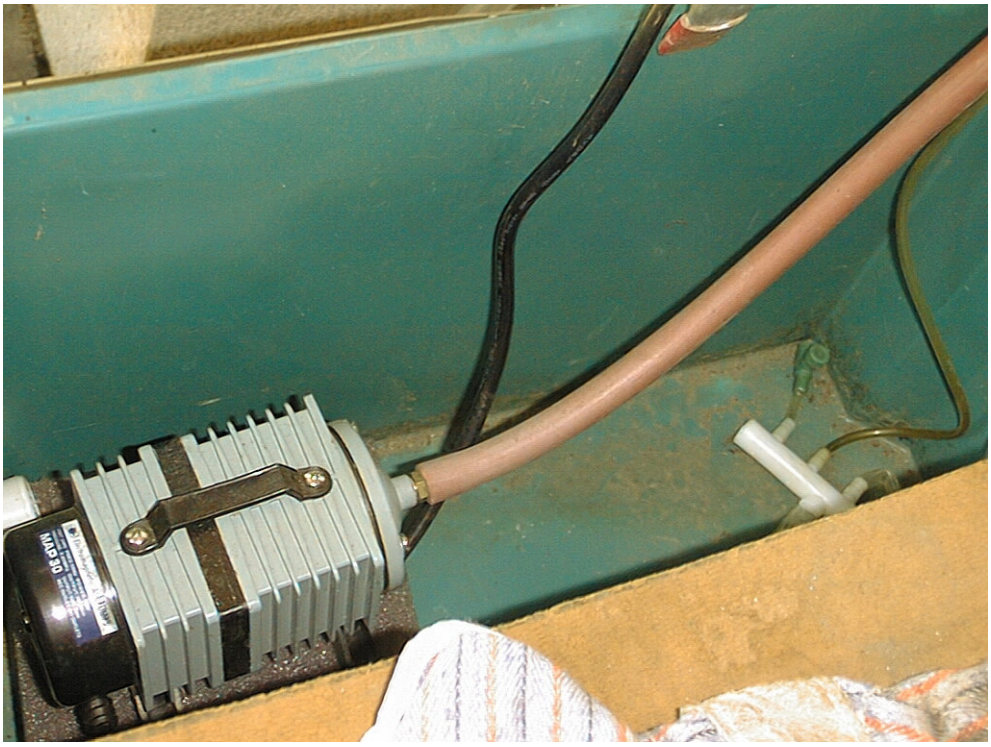

Fig II.3 Main air-supply

Fig II.4 Bilge pump and level switch mechanism for pumping treated effluent out

Fig II.5 Raw waste mix as prepared

Fig II.6 Final mature vermicasts

Fig II.7 The samples as they received treatment.

Left to right – raw blackwater, primary effluent and treated effluent (Sample numbers 157, 157A and 157B, respectively).

Fig II.8 Inside the upper compartment – V-hopper chamber

Fig II.9 Decomposing waste material in the lower compartment

Fig II.10 Perforated side and breaker mesh bar of the V-hopper chamber

Fig II.11 System internal view

APPENDIX III TEST METHODS EMPLOYED IN THE ANALYSIS OF DIFFERENT PARAMETERS

III.1 Physical Parameters –Liquid Samples

Total Suspended Solids

Method: Standard method 2540 D. Total suspended solids dried at 103-105 ^{o}C

Principle: A well mixed sample is filtered through a weighed standard glass-fibre filter and the residue retained on the filter is dried to a constant weight at 103-105 ^{o}C. The final increase in weight gives the TSS reading.

Apparatus:

Aluminium weighing dishes, desiccator, drying oven for operation at 103-105^{o}C, analytical balance, wide bore pipettes, graduated cylinder, pre-prepared glass fibre filter, filtration apparatus (suction flask, vacuum pump).

Procedure:

Sample volume (V) is selected to yield between 2.5 and 200 mg dried residue (based on trial and error or previous results). This varies between samples as the suspended matter differs. Filtering apparatus is assembled and suction is begun by first wetting the glass fibre filter with de-ionised water. The sample is stirred well for uniformity. A measured volume is pipetted out to the filter paper which is then washed with de-ionised water for complete drainage. Suction is continued for 3 minutes before removing the filter paper to the Al-weighing dish. The dish is weighed (A) and

placed in the dehydrating oven for at least an hour, cooled in the desiccator and weighed. This cycle is repeated until the difference in weight between measurements is less than 4% of the previous value. The final weight of the dish is noted as B.

The total suspended solids in mg/l is calculated as: (A-B) *1000 / V

Total Dissolved Solids

Method: 2540 C. Total Dissolved Solids Dried at 180^{o}C.

Principle: A well-mixed sample is filtered through a standard glass fibre filter and the filtrate is evaporated to dryness in a weighed dish and dried to constant weight at 180^{o}C. The increase in weight represents the total dissolved solids.

Apparatus:

Same equipments as for Total Suspended solids, additionally drying oven operating at 180^{o}C and Gooch crucible of 25-40 ml volume.

Procedure:

The glass fibre filter paper is prepared by washing with de-ionised water in the filtrating apparatus under vacuum. The dishes are heat cleaned at 180^{o}C for an hour in an oven. The dishes are stored in the desiccator. Sample size is chosen so as to yield 2.5 to 200 mg dried residue (V). The sample is stirred well for uniformity and a measured volume is applied on to the filter paper under vacuum. The filter paper is then washed with de-ionised water and suction is continued for 3 minutes for complete drainage. The total filtrate is transferred to the weighed evaporating dish, weighed (A) and evaporated to dryness in the drying oven for an hour at 180^{o}C. The dishes are cooled in the desiccator and weighed. The cycle is repeated until the

difference in the final weight is less than 4% of previous value. The final weight is noted as B.

The total dissolved solids in mg/l is calculated as: (A-B)*1000/V.

III.2 Chemical parameters

BOD_5: 5-day Biochemical (Biological) Oxygen Demand

STANDARD METHOD – for calibration and comparison for the Oxidirect and Oxitop units

The BOD test measures the molecular oxygen utilized during a specific incubation period for the biochemical degradation of organic material (carbonaceous demand) and the oxygen used to oxidize inorganic material such as sulphides and ferrous iron. The BOD concentration in most wastewater exceeds the concentration of DO available in an air-saturated sample. Therefore it is necessary to dilute the sample before incubation to bring the oxygen demand and supply to suitable balance. Nutrient elements and trace metals are added to the dilution water for bacterial growth. 5-day incubation has been accepted as standard, as complete stabilisation of a sample may require extended periods. DO is measured before and after incubation, and BOD is the difference of the values.

Cold storage of the sample is necessary if analysis is not begun within 2 hrs of collection. Else, storage at or below 4^oC is necessary. BOD bottles are glass bottles 60-ml or above capacity (300-ml preferred) incubated at 20 ± 1^oC.

Reagents and Dilution Water

1. Phosphate buffer solution: Dissolve 8.5 g of KH_2PO_4, 21.75 g K_2HPO_4, 33.4 g of Na_2HPO_4.7H2O and 1.7g of NH_4Cl in about 500 mL distilled water and dilute to 1L. The pH should be 7.2. Another method is dissolving 42.5 g KH_2PO_4 or 54.3 g of K_2HPO_4 in about 700 ml distilled water, with pH adjustment to 7.2 by adding 30% NaOH then diluting to 1L.
2. Magnesium sulphate solution: Dissolve 22.5g $MgSO_4$.7H2O in distilled water and dilute to 1L.
3. Calcium chloride solution: Dissolve 27.5g $CaCl_2$ in distilled water and dilute to 1L.
4. Ferric chloride solution: dissolve 0.25 g $FeCL_3$.6H2O in distilled water and dilute to 1L.
5. 1N neutralization acid solution: slowly while stirring, add 28 ml conc. H_2SO_4 to distilled water dilute to 1L.
6. 1N neutralization alkali solution: dissolve 40g NaOH in distilled water; dilute to 1L.
7. Sodium sulphite solution (for removal of any residual chlorine): Dissolve 1.575g Na_2SO_3 in 1L distilled water. Unstable solution- daily preparation is needed.
8. Glucose-glutamic acid solution (For seed control – not required in blackwater): Dry reagent-grade glucose and reagent-grade glutamic acid at 103^oC for 1hr. Add 150mg glucose and 150mg glutamic acid to distilled water and dilute to 1L. Fresh usage necessary.
9. Ammonium chloride solution (For seed control – not required in blackwater): dissolve 1.15g NH_4Cl in about 500ml distilled water, adjust pH to 7.2 with NaOH solution, dilute to 1L. Solution contains 0.3mg N/mL.

10. Dilution water: For 1L water, add 1ml each of phosphate buffer, $MgSO_4$, $CaCl_2$ and $FeCl_3$ solutions. A blank of this need be tested with the samples for DO-depletion over 5 days. If this value is more than 0.2 mg/l, discard the remaining water. Before using, bring the temperature to 20 $\pm$ 3^oC and saturate with air by shaking.
11. Dilution: 0.0 to 1.0% for strong industrial, 1 to 5% for raw and settled wastewater, 5-25% for biologically treated effluent and 25-100% for polluted river waters. Fill the bottle with enough water so that all air is removed.

$$BOD_5 = \frac{D_1 - D_2}{P}$$

Where D_1 is DO immediately after sample preparation, D_2 is DO after 5 d incubation at 20^oC and P is decimal volumetric fraction of sample used.

Chemical Oxygen Demand

Chemical oxygen demand is a measure of the oxygen equivalent of the organic matter content of a sample that is susceptible to oxidation by a strong chemical oxidant. There are different methods to measure this, such as the open reflux method (large sample volumes) and the closed reflux methods (titrimetric or colorimetric). Colorimetric measurements using a spectrophotometer are conducted in this project.

COD Reactor

The HACH Model 45600 COD reactor is a 25-well dry bath incubator that provides the 150^oC temperature environment for COD determinations. The ADJ (adjustable) mode, 100-155^oC can be adjusted; otherwise the preset 150^oC is used. A 2-hour timer is also incorporated. Use of polycarbonate safety shield is required.

HACH DREL 2400 Spectrophotometer

Method 8000 Reactor Digestion Method (3 to 150, 20 to 1500, and 200 to 15,000 mg/L COD)

Scope and Application: For water, wastewater, and seawater; digestion is required; 3–150 mg/L and 20– 1500 mg/L COD ranges are USEPA approved for wastewater analyses; 200–15,000 mg/L COD range is not USEPA approved.

1. Homogenize 100 mL of sample for 30 seconds in a blender. (For samples containing large amounts of solids, increase the homogenisation time.)

Note: If the sample does not contain suspended solids, omit step 1 and step 2.

2. For the 200–15,000 mg/L range or to improve accuracy and reproducibility of the other ranges, pour the homogenized sample into a 250-mL beaker and gently stir with a magnetic stir plate.

3. Turn on the COD Reactor. Preheat to 150 °C. Place the safety shield in front of the reactor.

4. Remove the caps from two COD Digestion Reagent Vials. (Be sure to use vials for the appropriate range.)

5. Hold one vial at a 45-degree angle. Use a clean volumetric pipet to add 2.00 mL of sample to the vial. This is the prepared sample.

Note: Use a TenSette pipet to add 0.20 mL for the 200–15,000 mg/L range.

6. Hold a second vial at a 45-degree angle. Use a clean volumetric pipet to add 2.00 mL of deionized water to the vial. This is the blank.

Note: Use a TenSette pipet to add 0.20 mL for the 200–15,000 mg/L range.

7. Cap the vials tightly. Rinse them with deionized water and wipe with a clean paper towel.

8. Hold the vials by the cap over a sink. Invert gently several times to mix. Place the vials in the preheated COD Reactor. The sample vials will become very hot during mixing.

9. Heat the vials for two hours.

10. Turn the reactor off. Wait about 20 minutes for the vials to cool to 120 °C or less.

11. Invert each vial several times while still warm. Place the vials into a rack and cool to room temperature.

12. Start Spectrophotometer. Touch Hach Programs. Select program 430 COD LR (Low Range) or 435 COD HR High Range/High Range Plus). Touch Start.

13. Clean the outside of the vials with a damp towel followed by a dry one to remove fingerprints or other marks.

14. Install the 16-mm adapter. Note: See Section 2.6 in the Instrument Manual for installation details. Place the blank into the adapter.

15. Touch Zero. The display will show: 0 mg/L COD.

16. When the timer beeps, place the sample vial into the adapter. Touch Read. Results will appear in mg/L COD.

17. If using High Range Plus COD Digestion Reagent Vials, multiply the result by 10.

Note: For most accurate results with samples near 1,500 or 15,000 mg/L COD, repeat the analysis with a diluted sample. The blank may be used repeatedly for measurements using the same lot of vials. Store it in the dark. Monitor decomposition by measuring the absorbance at the appropriate wavelength (420 or 620 nm). Zero the instrument in the absorbance mode, using a vial containing 5 mL of deionized water and measure the absorbance of the blank. Record the value.

Prepare a new blank when the absorbance has changed by about 0.01 absorbance units.

III. 3 Test Methods – Solid samples – as prescribed by AS 4454 – 2003

III.3.1. Methods for determination of pH, electrical conductivity and ammonium, nitrate and soluble phosphorous content (AS4454 Appendix A)

Principle: A sample of the product is shaken with water and the characteristics of the extract are measured.

Extractant: distilled or deionised water.

Apparatus:

1. Plastic extraction vessel with close-fitting lid and another plastic vessel.
2. Filtration equipment, low ash fast filter papers (Whatman no.41)
3. Centrifuge
4. Conductivity and pH meters
5. Means of nitrate concentration measurement (accuracy 5 mg/l), ammonium concentration measurement (accuracy 5 mg/l) and orthophosphate-P concentration measurement (accuracy 1 mg/l).

Procedure:

1. A representative sample is taken of volume approximately 1L.
2. The sample is moistened with deionised water until such time that water could be manually squeezed out of the sample.
3. The sample is mixed well. A volume of 100ml sample is taken in firmly packed form in a plastic vessel.

4. The compressed material is placed in the extraction vessel and 150 ml deionised water is added.
5. The vessel is sealed and shaken by hand, intermittently four times, for a period of 90 mins. The pH of the suspension is measured.
6. The solution is centrifuged at 3000 rpm for 5 mins and then filtered through the low-ash filter paper.
7. Measurements of electrical conductivity, nitrate, ammonium and orthophosphate concentrations of the filtrate are conducted as with the liquid samples.

III.3.2. Method for determination of moisture content (AS 4454 Appendix H)

Principle: The mass of a portion of the product is determined before and after it is dried in an oven.

Apparatus:

1. Forced draught oven capable of heating at 105^{o}C
2. Balance accurate to 0.5 grams
3. Cleaned and dried weighing dishes large enough to hold 350 ml castings

Procedure:

1. The mass of the weighing dish is determined (m1).
2. A representative sample of volume 350 ml (average of ranges prescribed in the standard) is placed in the dish and the combined mass determined (m2).

3. The dish is placed in the oven and the sample is dried until the mass becomes stable. This meant that 1hr of further drying didn't give a mass difference of more than 1%.
4. The final mass is determined (m3).

Calculation:

% Moisture of sample = {(m2-m3)/(m2-m1)}*100

III.3.3 Method for the determination of vermicast density and volume reduction

Principle: Pouring the sample into a rigid calibrated container and levelling the contents determine volume. The mass/volume ratio gives the product's density.

Apparatus: Rigid straight-sided pails of translucent plastic, calibrated in L; balance to weigh the sample.

Procedure:

1. The pail is cleaned and weighed.
2. The pail is calibrated by pouring water into it, to the nominal volume of sample taken (350ml).
3. The sample is placed in the pail loosely and the surface is levelled.
4. The pail is weighed. The difference in mass gives the weight of the sample at 350ml volume.
5. The density of the castings is determined = mass/volume.
6. The approximate volume reduction is calculated from the volumes of the raw input waste and the final product volume.

7. The approximate total mass of input solid waste is calculated from input data of solid waste and solid content of blackwater (m1). The total volume of input solid waste is then calculated as mass/density (v1).
8. The final castings are weighed (m2).

   Percent mass reduction = {1-(m2/m1)}*100.
9. The approximate total volume (v2) of the final castings is determined from the final mass of castings and the density (step 6).

   The percentage volume reduction is then = {1- (v2/v1)}*100.

III.4 Microbiological analysis

(Newton, K., 2003, *personnel comm.*)

The faecal coliform and E.coli method that AGAL used for microbiological samples, uses a defined substrate medium called ColiID. Samples are filtered through sterile membrane filters and the filter is placed on the medium, which is incubated at 44.5C for 24h. AGAL are NATA accredited for the tests on environmental waters. The method is validated against the APHA Standard Methods for Water and Wastewater MFC medium for faecal coliforms, and gives equivalent results.

"ColiID is supplied by bioMerieux and has approval from AFNOR for use with all foods for coliform and E.coli testing. It is supplied with a QC certificate for each batch purchased. In the laboratory, we run positive and negative control cultures, and reagent blanks with each days work. In addition, all equipment used is calibrated and monitored according to NATA requirements. All records of tests, calibrations and monitoring, including those generated during testing of the samples, are retained in laboratory archives".

APPENDIX IV PHOTOGRAPHS OF ANALYSIS INSTRUMENTS USED

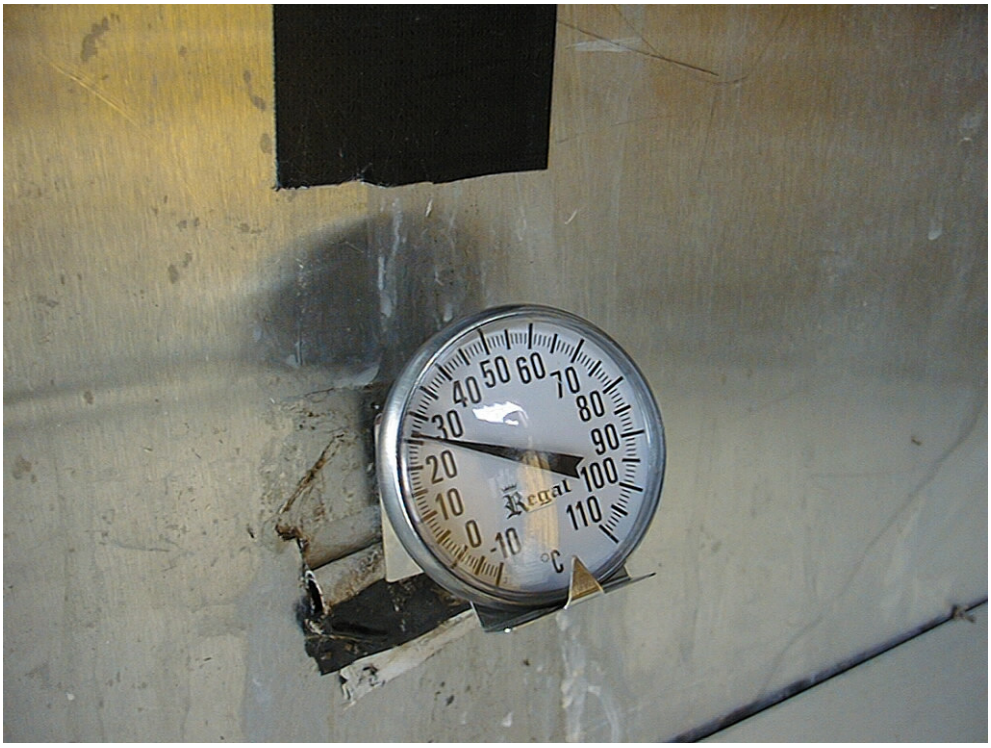

Fig IV.1 Bimetallic thermometer during operation

Fig IV.2 The pH meter during measurement

Fig IV.3 Conductivity and TDS measurement using HACH instrument

Fig IV. 4 Turbidity measurement instrument – HACH 2100N

Fig IV. 5 Instrument for DO measurement

Fig IV. 6 BOD_5 measurement using Oxidirect units

Fig IV. 7 BOD_5 measurement using Oxitop units

Fig IV. 8 COD digester

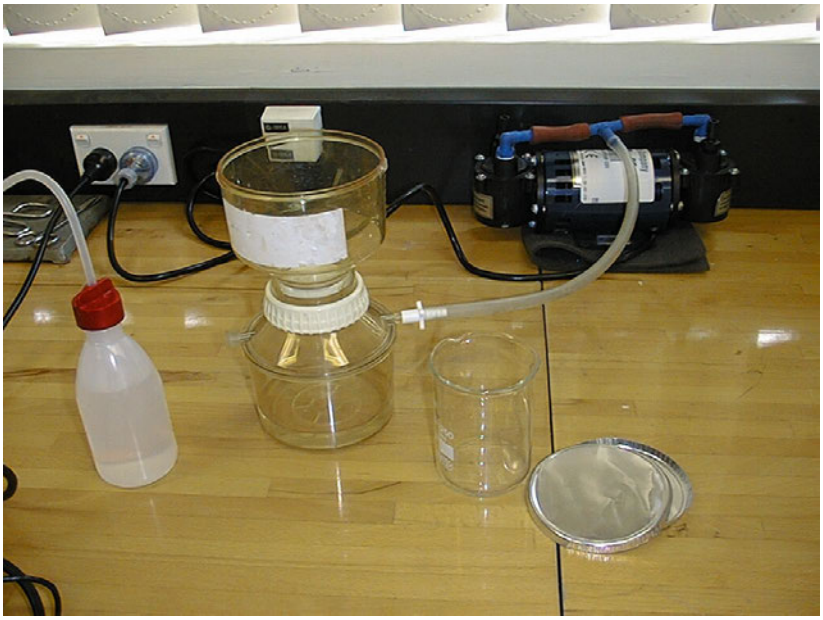

Fig IV. 9 Filtration equipment for TSS measurement

Fig IV. 10 Fan-forced dehydrating oven for drying filter papers and for moisture content measurement

Fig IV. 11 HACH DREL 2400 spectrophotometer with samples for measurement of nitrate, ammonium and phosphate

Fig IV.12 Vermicasts in water for extraction – measurements on solids according to Australian Standard AS4454-2003

APPENDIX V C:N VALUES OF COMMONLY COMPOSTED MATERIALS (refers to chapter 3)

[Envirocycle 2002]

Material	**C: N value**
Urine	8
Mixed abattoir waste	2
Liquid manure	2-3
Blood peal	3
Liquid pig manure	5-7
Faecal matter	6-10
Green vegetable matter	7
Bone meal	8
Liquid cow manure	8-13
Humus, loam	10
Aged composted manure	10-15
Fresh chicken manure	10
Household water purification sediment	11
Kitchen wastes	12-20
Grass clippings	12-25
Vegetable peelings, etc.	13
Chicken manure	13-18
Barnyard manure	14
Brewery wastes	15
Domestic animal excrement	15
Farm manure after 3 months storage	15
Vines of leguminous plants	15-18
Abattoir wastes (Stomach)	16-20
Alfalfa	16-20
Fresh manure with small amount of straw	20
Coffee grounds	20
Cow manure	20
Grass	20
Water hyacinth	20
Marsh cutting	20-30
Garden wastes	20-60
Potato vines	25
Horse manure	25
Manure with straw	25-30
Pine needles	30
Farm manure with large amount of straw	30
Black peat	30

Household waste	30-40
Brown or light peat	30-50
Foliage	30-60
City refuse compost	34
Residue of mushroom-growing medium	40
Straw from leguminous plants	40-50
Dead leaves	45
Oat straw	50-60
Rye straw	65
Millet straw	70
Wheat straw	70-150
Rice straw	100
Bark	100-130
Tree pruning waste	100-150
Sugar cane waste	150
Fresh sawdust	100-500
Decomposing sawdust	200
Cardboard	200-500

APPENDIX VI COLLECTION AND PRESERVATION OF SAMPLES

In case of pre-prepared/commercially available instruments/reagent sets are used, the sampling precautions/directions prescribed by the manufacturer of the instrument are followed. Generally, these are compared against Standard Methods table 1060: I for quality control.

Table VI.1 Collection and preservation of samples for analysis of different parameters

Parameter for determination	Container	Minimum sample size	Sample type	Preservation	Maximum storage
BOD_5	Plastic or Glass	1000	Grab or composite	Refrigerate	6 hrs
COD		100		Analyse as soon as possible OR add H_2SO_4 to less than 2.0 pH and refrigerate	7 days
Conductance		500		Refrigerate	48 hrs
Ammonia		500		Analyse as soon as possible OR add H_2SO_4 to less than 2.0 pH and refrigerate	7 days
Nitrate		100		Analyse as soon as possible OR refrigerate	48 hrs
pH		50	grab	Analyse immediately	15 mins
Total Phosphorous		100	Grab or composite	Analyse as soon as possible OR add H_2SO_4 to less than 2.0 pH and refrigerate	28 days
Solids (TSS, TDS)		200		Refrigerate	7 days
Turbidity		100		Analyse the same day, store in dark up to 24 hrs, refrigerate	24 hrs
DO	Glass	300	Grab	Analyse immediately	15 mins
Pathogens	P/G	100	Grab	Freeze	2 days

APPENDIX VII PAPERS PUBLISHED FROM THE RESEARCH PROJECT

- Panikkar A., Riley S and Shrestha S (2004): *Risk management in vermicomposting of domestic organic waste*. Environmental Health, vol 4, no. 2, pp 11-19. Australian Institute of Environmental Health.
- Panikkar A. and Riley S. (2003): *Organic On-site Waste Treatment for Houses*. *In:* Proceedings of Conference on future directions for On-site Systems "On-site'03"; Lanfax Science Laboratories, University of New England, Armidale, Australia. October 2003. Paper.
- Panikkar A. (2003): *Appropriate technology in domestic wastewater treatment*. 1st ISA Water and Wastewater Instrumentation Symposium, ISA (International Society for Instrumentation, Systems and Automation). Florida, USA. August 2003. Paper.
- Panikkar A. and Riley S. (2003): *Issues in blackwater reuse – an example of a treatment system*. International Civil Engineering Conference on Sustainable Development in 21st Century, Nairobi, Kenya. August 2003. Paper. ISBN: 9966-923-51-9.
- Riley S., Okalebo S. and Panikkar A (2003): *Multi-dimensional management of wastewater*. International Civil Engineering Conference on Sustainable Development in 21st Century, Nairobi, Kenya. August 2003. Paper. ISBN: 9966-923-51-9.
- Panikkar A. (2003): *Domestic sewage treatment by vermicomposting*. AWA Waterscape 2003 conference, Rosehill, NSW, Australia. May 2003. Presentation.
- Panikkar A., Shrestha S., Hackney P. and Riley S. (2003): *A residential blackwater and municipal solid waste treatment system – safety issues and risk management*. ORBIT 2003 conference, Perth, Australia. April – May 2003. Paper.
- Panikkar A. and Riley S. (2003): *Biological treatment of blackwater and mixed solid waste – an example of a treatment system*. ORBIT 2003 conference, Perth, Australia. April-May 2003. Paper.

- Panikkar A., Hackney P. and Riley S. (2002): *Onsite residential waste treatment via composting of blackwater and MSW.* Environmental Engineering Research Event 2002, Sydney, Australia. December 2002. Paper.

The first pages of published proceeding papers are reproduced in the following pages, and full papers are attached as a CD-ROM.