VERMICOMPOSTING TRIAL AT THE WORM RESEARCH CENTRE:

PART 1 - TECHNICAL EVALUATION

Technical Evaluation prepared by Jim Frederickson
Integrated Waste Systems
Open University

PART 2 - FINANCIAL EVALUATION AND MARKET POTENTIAL

Financial Evaluation and Market Potential prepared by Urban Mines Ltd
with contributions from Steve Ross-Smith WRC and Jim Frederickson (OU)

Funded by:

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Part One

Technical report prepared by Jim Frederickson

Integrated Waste Systems
The Open University

1. Foreword

The Vermicomposting Project has been a collaborative effort between Urban Mines Ltd, the Worm Research Centre (WRC) and Jim Frederickson of the Open University, with financial support being provided by ***shanks first***

Urban Mines is a not-for-profit environmental organisation concerned with the development and application of soundly based and practical approaches to the better management of the waste stream. The organisation works in partnership with a wide range of public, private and voluntary bodies in order to promote materials recovery, economic regeneration, job creation and environmental improvement. Most of their projects demonstrate a concern with the direct application of proven techniques and methods of management whilst others are more theoretical and conceptual.

Established in July 2000, the Worm Research Centre was developed from an existing worm farm in East Yorkshire that was struggling to find answers to the operational problems posed by outdoor worm farming. The aims of the Centre have evolved during the course of the project and it is now dedicated to providing objective information about large-scale vermicomposting systems operating under UK conditions.

Jim Frederickson is one of the UK's leading environmental scientists in the area of waste research, with over 20 years experience in managing, utilising and recycling biodegradable wastes. He was a founder member of the *Composting Association* in the UK and is now a Director. His research embraces many aspects of composting and organic waste utilisation including the environmental impact of organic waste processing systems. He is also a world authority on the use of earthworms in waste and environmental management and currently holds a UK patent relating to sustainable land restoration. He has been commissioned to undertake composting and environmental research for the UK Environment Agency and many leading companies and local authorities.

Having introduced the established practice of composting and vermicomposting in particular, this report presents the objectives of the present study. The findings of the study, both scientific and operational are then discussed in detail. Finally, after outlining the commercial possibilities of this research, recommendations are made for further work.

The research effort has involved contributions from many people within the three main organisations as well as a number of others in partner organisations. However, particular thanks is given to the following people: Steve Ross-Smith of the Worm Research Centre; Jim Frederickson of the Open University; Alan Phillips of Urban Mines; Paul Ellwood; Mike Waldron (M&M Worms); Graham Howell; Andrew Hobson; Professor Bill Radley (***shanks first***).

2. Executive Summary

The vermicomposting evaluation project described in this report was managed by Urban Mines Ltd, with funding from ***shanks first***. The project was carried out at the Worm Research Centre (WRC), which is managed by Steve Ross-Smith. The WRC provided support for the experimental research and also conducted the mechanisation trials. The scientific and experimental research was directed by Jim Frederickson with support from Graham Howell (Open University). The final report was written by Jim Frederickson with contributions from Steve Ross-Smith and Urban Mines Ltd (Financial Evaluation and Market Potential).

2.1 The project aims were:

i) The project sought to investigate the technical performance of outdoor vermicomposting, using a specifically designed bed system, which facilitated the research methods employed.

ii) The project identified low processing temperature as a limiting factor and investigated bed heating as a method of enhancing performance.

iii) The environmental impact of the outdoor vermicomposting system was evaluated in terms of leachate production and greenhouse gas emissions.

iv) Ways of mechanising the process were explored with particular emphasis on waste application to the processing beds.

v) The cost-effectiveness and market potential of outdoor vermicomposting systems was assessed, with particular regard to basing the study on new technical knowledge gained during the course of the project and practical techniques developed.

2.2 An outdoor, experimental vermicomposting system was designed and installed comprising 400 m^2 of waste processing beds. Each block contained a leachate drainage and collection system. The environmental impact of leachate and greenhouse gas emissions was undertaken. Beds were unheated apart from one complete block, which was heated during periods of cold weather. Air and bed temperatures were continuously monitored. Beds were inoculated with known densities of earthworms and populations were rigorously determined every eight weeks.

2.3 Following construction of the vermicomposting beds, the monitoring and experimental phase of the project commenced on 1st January 2001. The experimental phase duration was 56 weeks. The earthworm species used during the research was *Dendrobaena veneta.*

2.4 Air and bed temperatures were monitored continuously throughout the year. For the unheated blocks the average temperature of the beds over the coldest months was 7.2 °C. (around 60% of the year). The average temperature for the heated beds, during this same 30 week period, was controlled at 13.8 °C. For the hottest summer months, the average temperatures in the centre of the beds were around 20 –25 °C, but the maximum temperature recorded in the core of the beds was 32 °C. Optimum temperature for growth and reproduction of *Dendrobaena veneta.*is considered to be 20 –25 °C, whilst temperatures above 35 °C are thought to be lethal.

2.5 The performance of the unheated beds in terms of producing earthworms and offspring was relatively poor. For most of the beds, the weight of earthworms after six months had declined to around half of the initial weight. This was maintained for the duration of the project. The first significant numbers of cocoons and hatchling earthworms were recorded after 16 weeks and 32 weeks respectively. The adult population of earthworms began to increase after week 32 due to the presence of the newly produced hatchlings but then declined rapidly by the end of the project. It is estimated that the sustainable population of earthworms that this unheated system would support would be around 2 kg earthworms per m^3 of bed. This is similar to other commercial systems that were investigated and this would be adequate for processing a limited amount of waste and could produce some earthworms for harvesting in the longer term. Migration of earthworms out of the beds was observed and this would appear to significantly reduce earthworm numbers.

2.6 Heating the beds greatly increased earthworm populations compared with not heating. For example, after the first 24 weeks in operation, the number of hatchling earthworms in the heated beds was approximately 40 times greater than in the unheated beds. The heated beds show the potential to support a working earthworm density of at least 4 kg per m^3 of bed and this could be achieved after one year. It has been estimated that a possible 3 kg of mature earthworms per m^2 of bed could be harvested per year from such a system. However, this will only be achieved if earthworms are contained within the beds and migration prevented. Periodic mass migration of earthworms out of the beds was observed on one occasion resulting in the loss of an estimated one third of the population of adult earthworms.

2.7 The waste applied to the processing beds was potato slurry. When the heated beds had become established the beds processed approximately 1.2 kg potato slurry per m^2 of bed per day. This is equivalent to 0.6 kg of waste being processed by 1 kg of earthworms per day. It is estimated that at least 0.8 kg of waste per kg of earthworms should be achievable. For a heated bed with a working population of around 4 kg earthworms per m^2 of bed, a processing rate of approximately 3.2 kg waste per m^2 of bed per day should be possible.

2.8 The earthworm populations in the bedding material processed the waste potato slurry applied to the beds. The resulting mix of earthworm casts and bedding is termed vermicompost. When compared with typical green waste compost, the vermicompost was found to be richer in nitrogen and other valuable plant nutrients. If vermicomposts were eligible for the Composting Association

National Compost Standards scheme, the vermicompost produced during the project would have met the requirements for the parameters tested.

2.9 The environmental impact of vermicomposting was investigated. The vermicomposting system produced a significant volume of leachate during the project and the amount would have been broadly related to rainfall. While the leachate appeared to have the potential to pollute, it was found to be less polluting compared with typical leachate from composting sites. Vermicomposting leachate was found have a consistently low BOD, although COD was moderately high. It contained useful concentrations of plant nutrients making it potentially useful as a liquid fertilizing medium, if used with care.

Greenhouse gas emissions were monitored. Methane emissions were only detected during severe waterlogging of beds. However, research carried out during this project has identified vermicomposting as one of the most significant point sources of nitrous oxide emissions yet discovered. Nitrous oxide is a powerful greenhouse gas**.** There is a pressing need to investigate the extent of the problem as soon as possible and to identify mitigation options, if appropriate.

2.10 Research into mechanised methods of applying waste slurries to processing beds was undertaken and a successful system was developed.

2.11 A preliminary financial evaluation of the experimental vermicomposting system at WRC was undertaken. This suggests that the direct cost of operating the system is estimated to be within the range £8 to £30 per tonne of waste, depending on the income received for sales of worms and compost. At this time it is not possible to determine the overhead charges relating to the operation (business costs such as management, marketing and administration overheads). Figures for overheads quoted in this report are estimates only. The overhead charge is estimated to be approximately £15 per tonne. Hence, waste providers would need to pay a gate fee of between £23 and £45 per tonne in order to process suitable waste using the technology and systems described in this report.

Recommendations

It is recommended that vermicomposting systems should be operated as waste processing facilities that also have the potential to produce a limited amount of marketable earthworms.

It is recommended that research is undertaken into devising effective methods of containing earthworms in the processing beds. Despite installing a typical containment device for this project, a protruding lip on top of the beds, it was estimated that on one particular occasion, over one third of the adult earthworms migrated from an experimental block. Other separate mass migration events also occurred and this would appear to be expected for open-air systems, which flood periodically causing hostile bed conditions.

It is recommended that consideration is given to stabilizing conditions in processing beds so that the earthworm populations are given every chance to develop. In particular, periodic waterlogging of processing beds regularly took place during the project and prevention of rainfall entering beds should be a priority. If conditions in the beds are hostile for earthworms, it is likely that more effective containment methods will only lead to increased mortality.

It is recommended that processing beds be heated to at least 15 °C during the coldest months of the year. Methods of heating will vary depending on local conditions but insulating beds as a minimum first step should be a priority.

It is recommended that research is continued into identifying better methods of preparing and applying waste to the processing beds.

It is recommended that the emission and mitigation of greenhouse gases (nitrous oxide) from vermicomposting be investigated as a matter of priority.

It is recommended that increased research into large-scale vermicomposting is undertaken and that the findings be made readily available to the rapidly developing vermicomposting sector.

3. Introduction

Large-scale composting has been shown to be an important element in sustainable waste management for the UK and could have a vital role to play in meeting the obligations of the Landfill Directive. While it is clear that the composting sector is currently dominated by municipal windrow composting, there is enormous potential for the development of alternative composting systems such as vermicomposting.

There has been sustained growth in the composting sector for some time and over the last five years the number of operational centralised sites has grown on average by around 25% per annum. Moreover, the expansion has relied predominantly on the processing of relatively benign garden waste. This reliance on garden waste has led to the adoption of the low cost, very unsophisticated practice of open-air windrow composting at small-scale centralised sites and this approach currently dominates the UK industry. In 1999, 88% of waste composted was processed in open-air mechanically turned windrows. Despite an increase in the size of some sites, centralised composting sites still tend to be relatively small. In 1999, 56% of composting sites were each processing a maximum of only 7,000 tonnes of waste per year.

However, there is now evidence of the introduction of a wide range of novel and more advanced composting technologies, such as in-vessel and vermicomposting systems. While these systems currently form only a small part of the industry, evolving landfill and biodegradable waste legislation, and accompanying statutory targets, are likely to have a profound effect on the collection and processing of biodegradable waste, creating opportunities for the development of the composting sector. In particular, there is a pressing need for increased diversity in the composting sector and, as shown above, relatively small-scale and unsophisticated composting operations already play a very important role. This trend is likely to continue and is especially relevant for decentralised composting of putrescible and more difficult wastes such as food processing residues. Decentralised processing of industrial and commercial wastes is likely to be the focus of much attention in the next phase of composting developments in the UK.

Using earthworms to help process industrial and commercial wastes could have a very important role to play in the future. Many people are now familiar with the idea of using earthworms to compost domestic waste and many tens of thousands of small “worm compost bins” are owned by households up and down the country (See Figure 1).

Figure 1
Examples of home composting units

A list of suppliers of home wormeries and other worm composting units can be found in Appendix 10.

However, very few people know much about the widespread science and practice of using earthworms to compost waste on a large-scale. Vermicomposting is the name that is often applied to the process of composting organic waste using selected species of earthworms. Some of the existing commercial vermicomposting units in the UK are now capable of composting thousands of tonnes of waste per year and yet there is very little objective information about either the technical performance or the commercial viability of large-scale systems. The numbers and size of large-scale vermicomposting units appear to be increasing rapidly in line with increased composting and collectively, they should make a significant contribution towards sustainable organic waste management. However, the extent of this contribution is currently unknown and therefore the potential of vermicomposting cannot easily be assessed.

To a large extent, the interest in large-scale vermicomposting has arisen from the established but fragmented, worm-farming sector whose main aim was to produce earthworms for the fish bait market. However, recently the emphasis has changed and there is increasing interest in securing a gate fee for processing organic waste and in the marketing of the high quality compost that often results. Vermicomposting is the use of selected species of earthworms to help decompose and transform organic wastes into useful compost. However, as with all composting processes, it is the aerobic microorganisms, such as fungi and bacteria, which mainly decompose the waste; the action of the earthworms merely accelerates this process and also physically improves the characteristics of the final compost. Compared with municipal composting where waste is composted in batches, vermicomposting is a continuous process and is particularly suited to processing highly putrescible wastes. Very wet food-processing waste and paper sludges are particularly suited to vermicomposting and it is normal to apply these wastes on a frequent basis to earthworm processing beds in shallow layers. In general, vermicomposting operations tend to be located in rural areas, by farmers needing to diversify, and often they are close to small food processing plants and similar industries where low-cost, decentralised waste processing makes real sense.

Large scale vermicomposting and worm farming in the UK tends to be undertaken in very unsophisticated, relatively small, outdoor worm beds and the performance of these systems is therefore temperature and weather dependent. There has been a significant amount of scientific research undertaken into the process of using earthworms to decompose organic materials but most of this has been based on laboratory studies carried out under optimum conditions. Little research has focused on practical applications of vermicomposting but it is clear from existing research that most outdoor vermicomposting systems in the UK are operating under sub-optimal conditions. There would appear to be considerable opportunities to enhance the vermicomposting process, both scientifically in terms of improving the efficiency of the process and technologically so that the system can be operated more cost-effectively. In particular, vermicomposting could offer considerable benefits when operated in conjunction with other processing technologies such as in-vessel composting systems.

The trend towards more and larger vermicomposting units, allied to the changing emphasis from earthworm production to waste management, highlights the pressing need to understand more about these types of facilities. Although many existing vermicomposting units attempt to combine earthworm production with waste processing, these two requirements are conflicting. This is because earthworm production is best achieved using low earthworm densities during vermicomposting with frequent earthworm harvesting while maximising waste processing rates depend on maintaining high earthworm densities. Hence, there is a clear need to identify the main aim of the process and this should have a profound effect on how the vermicomposting system is operated and how it is subsequently evaluated.

In general very little is known about the size and characteristics of the sector, the commercial viability of vermicomposting and the technical performance of the production processes employed. In addition, very little research has been undertaken into the environmental impact of large-scale vermicomposting and as a result, there is considerable uncertainty surrounding many aspects of planning and licensing.

One organisation that aims to address these issues is the *Worm Research Centre*. The Centre is based around an existing worm farm in Yorkshire and is dedicated to providing objective data on large-scale vermicomposting systems, operating under UK conditions. A key aim of the Centre is to contribute to greater public understanding of vermicomposting systems; their performance and their use. In the longer term, it is envisaged that the facilities and expertise at the *Worm Research Centre* will be made available to the waste management industry to investigate sustainable vermicomposting of a wide range of organic wastes.

This report is an account of an eighteen month project conducted by the *Worm Research Centre*. The project sought to investigate the technical performance and enhancement of outdoor vermicomposting and explore ways of improving its commercial viability, through such means as increased levels of mechanisation. The environmental impact of vermicomposting was also rigorously monitored and it is envisaged that the findings from the project will significantly contribute to the planning and licensing debate. The project and the subsequent report represent the first attempt, in the UK, to rigorously evaluate the performance of large-scale outdoor vermicomposting, with the aim of making the information available to the industry. Hence, this report is not written with the intention of being a definitive guide to “worm farming” or waste processing. It is hoped that the report will be helpful to existing and prospective operators of vermicomposting systems and that it will enable everyone in the sector to ask more informed questions about how vermicomposting is carried out. Equally, this applies to those involved with regulating and licensing such operations and it is hoped that they will benefit from the research into environmental impact.

The project was managed by Urban Mines Ltd., with funding from ***shanks first***. The *Worm Research Centre* is managed by Steve Ross-Smith, who also provided support for the experimental research and conducted the mechanisation trials. The scientific and experimental research was directed by Jim Frederickson with support from Graham Howell (Open University). The report was written by Jim Frederickson , Integrated Waste Systems research group, The Open University, Walton Hall, Milton Keynes, MK7 7DL. Tel: (01908) 653387, e-mail: j.frederickson@open.ac.uk, with input from WRC and Urban Mines Limited.

4. Background to Vermicomposting

Using selected species of earthworms to help compost organic waste, known as vermicomposting, is a process that has been widely adopted throughout the world. Indeed, many countries such as Australia, the USA and several European countries have developed thriving vermicomposting industries. The roots of vermicomposting are thought to stem from the established business of vermiculture, which is the breeding of earthworms mainly for the fishing bait market. In recent years, growing awareness of the ability of earthworms to decompose and stabilize a wide variety of wastes has changed the focus of the industry from producing earthworms to producing compost. However, in practice it is almost impossible to separate the production of earthworms from the processing of waste and many vermicomposting businesses focus on both aspects. However, maximum earthworm production is best achieved using low earthworm densities during vermicomposting coupled with frequent earthworm harvesting. Maximising the waste processing rate depends on maintaining high earthworm densities throughout the vermicomposting process and this is clearly in conflict with producing maximum earthworm biomass from the system. Many years of experience of vermicomposting has shown that it can be a useful method of composting and one that is suited to a wide variety of wastes but while it has some advantages compared with traditional composting, it also has many disadvantages.

Unlike windrow composting, vermicomposting has the potential to produce an additional product in the form of earthworms and many vermicomposting systems have been started or sold on the basis of the profits to be earned from selling these. However, in an attempt to sell commercial vermicomposting systems, exaggerated claims have often been made about the ability of the vermicomposting process to produce large numbers of marketable earthworms and to transform a wide variety of wastes into premium quality vermicompost. While some of these claims are justified, many have not been adequately researched, especially on a large-scale and under sub-optimal processing conditions.

Vermicomposting and traditional composting

Vermicomposting is the use of selected species of earthworms to help decompose and transform organic wastes into useful compost. With traditional composting, the compost piles are mixed and aerated mechanically but with vermicomposting it is the earthworms that fragment, mix and help aerate the waste. There are many different methods of vermicomposting, making it impossible to present a definitive guide to best practice. Systems will vary depending on whether the aim is to produce vermicompost or earthworms, or both.

While vermicomposting and composting both involve the aerobic decomposition of organic matter by microorganisms, there are important differences in the way the two processes are carried out. The most notable being that vermicomposting is carried out at relatively low temperatures (under 25°C), compared with composting, where pile temperatures can exceed 70°C. The intention with traditional composting is to stack waste material in sufficiently large piles so that the heat produced in the intense breakdown of organic matter is retained in the compost pile. This temperature increase stimulates the proliferation of heat loving (thermophilic) microorganisms and it is mainly these that are responsible for the decomposition. With vermicomposting it is vitally important to keep the temperature below 35°C, otherwise the earthworms will be killed. It is the joint action between earthworms and the aerobic microorganisms that thrive in these lower temperatures (mesophilic) that breaks down the waste. Hence it is common with vermicomposting systems to apply waste frequently in thin layers, a few centimetres thick, to beds or boxes containing earthworms in order to prevent overheating and to help keep the waste aerobic.

It is difficult to directly compare composting with vermicomposting in terms of the time taken to produce stable and mature compost products. With vermicomposting, particles of waste spend only a few hours inside the earthworm's gut and most of the decomposition is actually carried out by microorganisms either before or after passing through the earthworm. Hence, earthworms accelerate waste decomposition rather than being the direct agent. With in-vessel and windrow composting it usually takes at least six to twelve weeks to produce a stable compost and research suggests that vermicomposting takes around the same time. However, processing rates will crucially depend on many factors such as the system being used, the processing temperature and other factors, the nature of the wastes and the ratio of earthworms to waste.

One advantage that vermicomposting has over composting is that a net excess of earthworms can be produced and these may be harvested for a variety of purposes. It should be noted that it can take many months or even years to build up a large working population of earthworms capable of vermicomposting significant quantities of waste. Vermicomposting does have one serious disadvantage and this relates to the destruction of human and plant pathogens that can be present in some wastes. Destruction of most pathogens is more easily achieved in windrow composting due to the high operating temperatures and the intense microbial reactions taking place. Although the destruction of human pathogens has also been shown to be very effective with vermicomposting, elimination of pathogens requires very effective management of the vermicomposting process. It is often recommended that wastes, such as sewage sludge, which are known to contain human pathogens, are either pre-composted before vermicomposting or else the resulting casts should be sterilized before use.

Large-scale vermicomposting systems

The most widely used vermicomposting system worldwide is the bed method, which involves applying thin layers of waste material to the surface of beds containing relatively high densities of earthworms. New layers of waste are applied to beds on a regular basis and the earthworms move upward into the fresh waste to feed and to process the material. Earthworm numbers increase as more waste is applied until a limiting density is reached and harvesting of earthworms or dividing of beds to form new beds is usually undertaken. See Gaddie and Douglas (1978) for typical bed designs. The main disadvantage with this bed system is that low-level beds take up a considerable area of ground in relation to the relatively small amount of waste processed. It has been estimated that a bed vermicomposting system could take up to six times more land area to process the same amount of material compared with windrow composting. Because of this, more sophisticated stacking systems have been proposed since they take up less ground area.

Worldwide, a wide variety of vermicomposting systems have been invented and installed. Figure 2 shows a large-scale operation in Korea based on a series of conveyer belts containing sewage sludge and earthworms.

Figure 2
Conveyor system in Korea

Automated reactor systems have been installed which allow waste to be fed from a gantry above the reactors while finished vermicompost is collected from the base using breaker bars. Such a vermicomposting system was installed in 1991 at Montelemar, France to process organic matter from the town's household waste stream. Mixed waste is sorted and then pre-composted for 30 days before being vermicomposted for 60 days by an estimated 1,000 million earthworms.

Around 27% of the total waste stream is converted in a number of reactors to good quality vermicompost which is then bagged and sold.

Separating the processed waste (vermicompost) from the earthworms at the cessation of processing is often performed manually but for many years earthworm harvesting machines have been commonly available in the USA and other countries. Typical trommel and vibrating screen harvesters are shown in Figure 3.

Figure 3
Typical worm/compost harvesters

In many countries, decentralised waste processing may be undertaken using small-scale reactor systems as shown in Figure 4 (see for example http://www.vermitechsystems.com/). Some versions tend to be fully automated but often they can be no more than simple containers, similar to compost bins, but supplied with earthworms. A feature of reactor systems is that they are designed to be used continuously rather than on a batch operation.

Figure 4
Small-scale reactor system

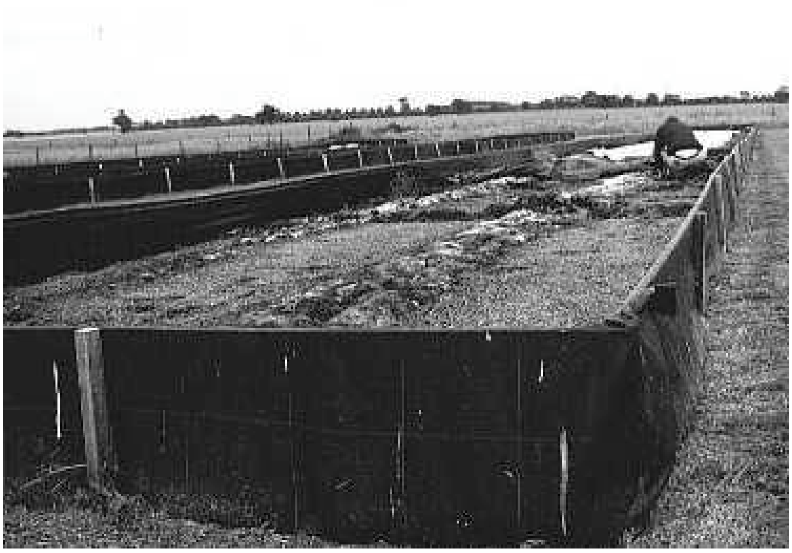
Typical vermicomposting systems in the UK

The trend towards more and larger vermicomposting units, allied to the changing emphasis from worm production to waste management, highlights the pressing need to understand more about these types of facilities. In general very little is known about the size and characteristics of the sector, the commercial viability of vermicomposting or the technical performance of the production processes employed. In addition, there is considerable uncertainty surrounding many aspects of planning and licensing.

In the UK, although the number of indoor or enclosed systems appear to be increasing, most vermicomposting systems would appear to be based on either outdoor windrows or covered shallow beds. There is very little evidence of mechanisation and the use of labour saving equipment, such as earthworm harvesters, is rare. Figure 5 shows the layout of a typical, very unsophisticated, outdoor vermicomposting bed in the UK. Strips of waste material on the surface of the bedding material can be seen. The bed shown is approximately 5 metres wide, 50 metres long and 0.5 metres deep. The beds typically comprise wooden sides covered in a woven semi-permeable fabric containing coir or shredded wood chip bedding placed directly on the soil surface.

When installed, the bed would have been inoculated with starting culture of adult earthworms at a density of approximately 0.5kg earthworms per m^3 of bed. The suppliers of similar systems typically claim that the rate of increase of the starter earthworm inoculum is such that adult earthworms (weighing in excess of 1g each) may be harvested after six months of installation and that regular harvesting is possible. A commonly reported problem with such systems is that growing adult earthworms of the correct size is difficult. Some operators have

Figure 5
Typical bed system



installed separate “fattening” houses where harvested immature earthworms are allowed to grow larger under lower density conditions and with the application of some background heating.

Up until recently, most vermicomposting facilities were modest in size with bed areas around 1,000 m^2 but there is now a trend towards much larger units, as much as ten times this size. Very large units can process large amounts of waste, of the order of thousands of tonnes per year, making them comparable to many of the smaller municipal composting operations.

There is very little information available on the nature of the vermicomposting industry in the UK and what little exists is considered to be commercially sensitive. There are at least four major suppliers of large-scale vermicomposting systems currently operating. In year 2000, a series of interviews were conducted on behalf of WRC to ascertain the approximate number of vermicomposting systems supplied by one company. At that time, there were around 90 individual operators with 81,000 m^2 of beds. The total investment would have exceeded £1.25 million.

Scientific and technical aspects of vermicomposting

A number of factors affect the life cycle of earthworms and hence determine the rate of waste processing, vermicompost output and the number of earthworms that are produced. In particular, temperature, moisture, waste characteristics and earthworm density are all important.

There is little doubt that maintaining vermicomposting systems at a constant temperature of around 20°C would give maximum vermicompost output and ensure maximum earthworm growth and reproduction. In UK conditions, if vermicomposting is carried out in unheated beds they are likely to produce significantly lower outputs than for beds operating under optimum conditions.

Earthworms prefer material that is fairly damp, in the range 70 - 90% moisture. Hence there is usually more of a need to add more moisture to the waste material before and during vermicomposting compared with traditional composting. Since moisture is not driven off by high temperatures, as with composting, the finished vermicompost can be quite moist, and often the conversion of waste to vermicompost results in only a small weight loss, typically around 10%.

Earthworms will process more waste and will grow and reproduce more quickly when fed some wastes compared with others. Sewage sludge, animal manures, paper pulps, processed food slurries, brewery waste, mixed household waste, garden and vegetable wastes and many other biodegradable materials have been used on a large scale to produce vermicompost and to breed earthworms. Vermicomposting is similar to traditional composting in the sense that materials with carbon to nitrogen (C:N) ratios in the range 15 – 35:1 are considered to be suitable. In general, fresh, finely shredded organic materials which, decompose easily will sustain the greatest numbers and diversity of microorganisms and this in turn will result in rapid decomposition and produce the highest earthworm growth and reproduction.

The density of earthworms in any vermicomposting system is related to the rate of waste processing and if vermicompost production is the main aim then it is advisable to maintain a high density of mature earthworms. However, high earthworm densities will eventually reduce the number of earthworms produced, by regulating growth and reproduction. Hence, if the main aim is to produce a net surplus of earthworms, comparatively low densities of immature earthworms should be used. Equally, regular harvesting of earthworms and cocoons should be carried out to maintain this low density at all times.

Earthworm species

Over 3,000 individual species of earthworms have been recorded throughout the world but in the UK only around 28 species have been found or imported. It is useful to divide these various species into three broad categories depending on habitat and ‘lifestyle’. It is only the litter dwelling species that are used for vermicomposting.

Litter dwelling earthworms (*Epigeic* species)

There are several deeply pigmented or red species that normally live in the rotting litter or organic matter on the surface of soils. They grow and reproduce very prolifically compared with true soil dwelling earthworms. The three species most commonly used in vermicomposting in the UK are *Dendrobaena veneta* (blue nosed worm), *Eisenia fetida* (tiger or brandling worm), *Eisenia andrei* (red tiger worm). In warmer countries other tropical species such as *Eudrilus eugeniae* have been farmed.

Topsoil dwelling earthworms (*Endogeic* species)

Just below the surface live another group of small earthworms, in the first few centimetres of topsoil. They improve soil structure in the root zone of plants and recycle dead organic matter. One notable species is the 'green worm', *Allolobophora chlorotica*.

Deep burrowing earthworms (*Anecic* species)

Some of the most important species live deeper down in the soil profile in permanent vertical burrows that can be up to two metres long. They help create topsoil by dragging dead organic material from the soil surface down into their burrows, ingesting it along with soil and then egesting the mixture back on the surface as nutrient-rich earthworm casts. Species in this category are highly valued and have been successfully bred for land restoration projects. Two of the more beneficial species are *Lumbricus terrestris* (the lob worm or 'common earthworm') and *Aporrectodea longa* (black headed worm).

Earthworm life cycle

Vermicomposting species such as *D. veneta* and *E. fetida* can grow to weights of around 4g and 2g respectively and can live for up to three years under ideal conditions. When sexually mature they will develop a noticeable swollen band on their body, called the clitellum ('saddle') and after mating they roll a band of mucus from this organ, off their bodies, forming a roughly spherical cocoon, from which offspring will hatch. Earthworms are hermaphrodites, having both male and female sex organs but in general they need to mate with other earthworms of the same species to produce offspring. After mating, each earthworm will produce cocoons. Some species produce only one or two hatchlings per cocoon (*D. veneta*), while others can produce several such as *E. fetida*. Earthworms can breed all year under ideal conditions but cocoon output is known to decrease rapidly (reproductive fatigue) after a period of prolific production. For example, in sewage sludge *E. fetida* reproduced for around one year but maximum cocoon production occurred when the earthworms were aged between 9 - 11 weeks and declined significantly thereafter. Table 1 shows the life cycles and the maximum reproductive output for two species fed on animal and vegetable waste.

Table 1
Life cycle and maximum cocoon production under ideal conditions (Edwards, 1998)

Species	Time to sexual maturity (days)	Cocoons per worm per week Produced	Proportion of cocoons hatching (%)	Young per cocoon produced	Time for cocoons to hatch (days)
Dendrobaena veneta	57 - 86	1.6	81.2	1.1	40 - 126
Eisenia fetida	53 - 76	3.8	83.2	3.3	32 – 73

Best conditions for vermicomposting

Temperature

The optimum range for culturing *D. veneta* and *E. fetida* is considered to be around 15 - 25°C. Temperature during vermicomposting has both positive and negative effects on growth and reproduction at different stages of the life cycle. Below 15°C, earthworms grow relatively slowly and produce few cocoons but as the temperature is increased so does growth and reproduction. For example *E. fetida* is known to produce up to four times more cocoons at 25°C than at 15°C. At 25°C, earthworm mortality also rises and the viability of cocoons and the number hatchlings per cocoon decrease significantly. The time taken to complete the life-cycle of *Dendrobaena veneta* has been studied in the laboratory and was found to be temperature dependent. It took 150 days to complete at a constant 15 °C but only 100 days at 25 °C. This confirms the positive effects that increased temperature has on most aspects of the life cycle. Temperatures in excess of 30 - 35°C are lethal to earthworms.

Moisture content

The moisture content of organic material fed to earthworms can greatly affect growth and reproduction but it is impossible to be precise about the optimum level. In general, earthworms prefer material that is fairly damp, in the range 70 - 90% moisture.

Earthworm density

Higher densities will increase the rate of vermicompost production but there are maximum densities that can be achieved in processing beds or boxes. This is known as the carrying capacity of the system and is related to a host of factors such as the nutritional value of the waste being processed and the processing temperature. For *E. andrei* this is 2 kg per m^2 of bed when fed horse manure, which is low in nutritional value and 7 - 11 kg per m^2 of bed when fed pig manure. Lower densities are needed for best earthworm production; for example decreasing the number of *E. andrei* from 40 to 10 per kg of fresh waste increased their growth rate by 50% and led to a fivefold increase in the number of cocoons. Typical working densities for particular vermicomposting systems have been reported to be between 1 and 4 kg earthworms per m^2 of bed.

Suitable wastes

In order to produce finely-divided vermicompost, earthworms must ingest the waste. For this to happen successfully, more resistant organic materials need to be shredded or pre-composted first. Most species used for vermicomposting can convert between one quarter and twice their own weight of waste per day into vermicompost depending on waste characteristics and processing conditions. These factors determine the rate of earthworms produced as well as affecting the amount of waste produced. Using sewage sludge instead of horse manure increased earthworm biomass by 250%. Feed that has aged or been pre-composted has been shown to be much less nutritious than fresh material. For example, feeding green waste to *E. andrei* that had been composted for two weeks resulted in only half the number of cocoons being produced compared with feeding fresh waste. Frequent feeding is an important factor for good growth and reproduction and replacing worm worked food with fresh food every two weeks has been found to double cocoon production compared with replacing every four weeks. The acidity or alkalinity of wastes used in vermicomposting, providing the waste pH is in the range 5 – 9, appears not to significantly affect growth and reproduction. However, wastes heavily contaminated with heavy metals could be toxic to earthworms and comparatively low concentrations of some metals have been shown to adversely affect growth and reproduction.

Environmental impact of vermicomposting

As with all waste processing activities, vermicomposting has the potential to have a high environmental impact. Compared with other waste related sectors such as municipal composting or recycling, the environmental impact of large-scale vermicomposting has not been thoroughly researched. In particular, the processing of many controlled wastes is known to produce odour problems and some processes are associated with bio-aerosol emissions and leachate production. The equipment processing wastes has also been found to produce noise and dust problems as well as the emission of Volatile Organic Compounds (VOCs). A review of environmental impact related to waste processing is beyond the scope of this report but two aspects of environmental impact will be briefly highlighted because they closely relate to vermicomposting. Leachate production and the potential to emit greenhouse gases are important considerations.

Leachate from vermicomposting operations is often regarded as beneficial in the sense that when collected it can be used a liquid fertiliser, often called “worm tea”. While this is true, the leachate also has the potential to pollute when not collected and used positively. Previous studies using earthworm reactors to help treat dilute sewage found that while such reactors achieved good results, the resulting leachate was still polluting in terms of Biological Oxygen Demand (BOD), Chemical Oxygen Demand (COD) and nitrate concentration.

The emission of greenhouse gases from waste processing plants is now receiving considerable attention. A prime factor in the move away from landfilling waste to more sustainable methods of treating biodegradable waste, is the minimisation of greenhouse gas emissions, in particular methane. However, greenhouse gas emissions have been monitored at large-scale composting sites and methane and nitrous oxide, which is a more powerful greenhouse gas compared with methane, have been detected. Methods for reducing the emission of these gases from composting plants, is being investigated. No research has been published into the potential for vermicomposting systems to emit greenhouse gases. However, earthworms are associated with high levels of nitrous oxide release from forest soils. Equally, vermicomposting systems, because they are designed to be continuous processes and operate at high moisture levels, could provide ideal conditions for methane production.

Outputs from Vermicomposting

Vermicompost

Vermicompost is the matured, processed material that is egested from earthworms as casts. As earthworms feed on the rich diet of organic matter and micro-organisms in waste, this ingested material is finely ground by the earthworms gut. This helps micro-organisms decompose the organic matter and stimulates mineralisation of complex compounds into simple nutrients, easily utilised by plants. At the same time the organic matter and microbial cells are glued together by the secretions from the earthworms gut forming casts. The amount of time that the waste spends in the earthworm gut is only a few hours and therefore the egested cast material is very microbially active and continues to decompose for some time. Once matured, the casts are known as vermicompost, which can have excellent physical and chemical characteristics. Compared with windrow composts, vermicomposts are likely to contain higher levels of nitrogen because vermicomposting temperatures and nitrogen losses are typically much lower.

The nature of the feed material or waste will often determine the characteristics of the final vermicompost with high nitrogen material, such as food processing waste, giving vermicompost rich in plant available nutrients. Equally, although it is known that some earthworm species can selectively accumulate and concentrate particular heavy metals from industrial sludges, it is not possible to use earthworms to “clean up” contaminated wastes.

As with most waste-derived composts, vermicompost when used as a plant growth medium is likely to produce better results when amended with other materials. This is because the vermicomposts made from many wastes can be very rich in nutrients and too alkaline for optimum plant growth. Vermicompost mixes have sometimes performed better than commercial and compost-based products. Mixing vermicompost with equal volumes of coir, for example, is usually sufficient to produce good plant growth media but a feature of vermicomposts is that often only small amounts in blended plant growth mixes (10 - 20%) give excellent results.

Many factors will determine how much earthworms will ingest per day and how much vermicompost can be produced per m^2 of bed in a certain time. For example, earthworms have been reported to eat twice their weight of sewage sludge per day and in another study a feeding rate of 0.8 kg biosolids (sewage sludge) per kg of earthworms was found. In a further experiment with biosolids, it was reported that the best vermicompost was obtained with a feeding rate of 0.75 kg biosolids per kg of earthworms per day from a bed stocked with 1.6 kg earthworms per m^2. In an experiment using precomposted vegetable waste, only 1.5 kg per m^2 of bed per day was converted to vermicompost by a bed stocked with 4 kg of earthworms per m^2.

Earthworms

It is an important feature of sustainable vermicomposting systems that the earthworm population should at least remain stable or preferably increase to allow for expansion of the operation. Moreover, if the emphasis is placed on producing a large number of earthworms for selling in starter kits or for use in smaller domestic worm composters, it is particularly important to provide the earthworms with the best conditions for growth and reproduction. World-wide, exaggerated claims are often made for very high rates of earthworm reproduction as a means of marketing vermicomposting systems. Population increases in excess of 1,000 fold in one year have been promised - under ideal conditions. Unfortunately, ideal conditions are seldom achieved in commercial vermicomposting operations and it is more likely that only modest increases in population can be achieved in practice.

Reported increases in earthworm biomass and population from vermicomposting systems are very variable and probably reflect different systems, temperature and breeding conditions and wastes. For vermicomposting beds fully stocked with a high density of earthworms *(E. andrei*), the amount of earthworm biomass harvested per year was found to be 6 kg per m^2 of bed when fed horse manure and 18 kg per m^2 of bed when fed pig manure. For beds stocked with an initial, low density starter culture of earthworms, a 10 fold increase in population in 16 months was found for *E. fetida* when fed sewage sludge. It must be remembered that most of the increase in population would have been in the form of very small, juvenile and hatchling earthworms and these can take many months to grow into mature adults, depending on conditions. Vermicomposting household waste for six months using *E. fetida* resulted in a 3 - 4 fold increase in earthworm biomass and an 80 fold increase in earthworm population. Again, it is important to note that vermicomposting can result in very impressive increases in earthworm numbers, due to large numbers of juvenile and hatchling earthworms being produced. However, increases in the total weight (biomass) of earthworms often takes significantly longer because of the time it takes for very young earthworms to grow to maturity. Unfortunately, high earthworm density, poor nutrition and other factors may prevent significant weight gain from happening and total biomass may stabilize, not increasing to any marked extent.

5. Approach to the research programme

The overall project was carried out in a number of phases and comprised several technical and non-technical components. The initial phase of the project comprised a scientific literature review focusing on vermicomposting research and practice. At the same time a number of interviews were conducted with existing operators and key stakeholders in the waste management and vermicomposting industries in order to generate background information on the commercial and practical operation of the vermicomposting sector. Lastly, two vermicomposting operations, which had been in existence for two years were selected for technical evaluation and the operators were interviewed. The processing beds and associated facilities at these establishments were extensively sampled and monitored to assess typical processing capacities and characteristics. Arising out of this background research a number of important issues were identified and these are listed below.

5.1 Identification of research issues

i) Most objective scientific literature and data relating to vermicomposting systems was derived from laboratory-based research projects, which were carried out under optimum operating conditions. The quoted performance of commercial vermicomposting systems is typically based on optimised research data. Little research had focused on large-scale systems operating under adverse weather conditions and it is highly likely that most outdoor UK vermicomposting systems are operating under sub-optimum conditions and hence, performing very poorly compared with expectations.

ii) Two major practical problems with existing vermicomposting systems were frequently cited by operators. Firstly, the poor construction and design of typical beds often led to problems with inadequate drainage and difficulty in applying waste to the beds. Secondly, many of the activities associated with operating current vermicomposting systems were perceived to be labour intensive and costly. These are activities such as applying waste to the beds and periodic harvesting of earthworms by hand. Better bed design to minimise operational problems and to enhance waste processing rates and earthworm output was considered by many to be very important. As was investigation of new methods mechanising the various processes involved with vermicomposting.

iii) No objectively verified published information relating to the performance of large-scale vermicomposting systems operating under UK conditions was available to prospective purchasers of such systems. This lack of information appeared to extend to basic operating characteristics (e.g. bed temperature, moisture and feed specifications) and performance levels such as rates of earthworm production and waste processing rates.

iv) Many existing commercial operators of worm composting systems expressed disappointment with the poor outputs from the business and the fact that higher levels of labour, time and funding were required than had been forecast. Considerable claims about the profitability of worm farming enterprises are often made by suppliers of systems but poor performance in practice appears to cast considerable doubts on the cost-effectiveness of commercial operations. No objectively verified published information relating to the financial viability of large-scale vermicomposting systems operating under UK conditions was available to prospective purchasers of such systems.

v) Large-scale vermicomposting systems operating under UK conditions tended to be almost exclusively based on the unsophisticated model of open-air, bed systems containing a bedding material and an inoculum of earthworms. Biodegradable waste is then applied to the surface of the beds and this is subsequently digested by the earthworms, decomposed and treated. Since beds are designed to be placed directly on the soil surface any bed leachate from excessive rainfall runs directly to ground. As a result of the application of biodegradable waste as a feed material for the earthworms, a key feature of these vermicomposting systems is that the earthworm population should increase over time and may be harvested and sold. However, a number of operators of such systems when interviewed expressed concern that they failed to perform as well as promised, especially in terms of earthworm production. Systems were also reported to take considerably longer than expected to become fully operational. Preliminary examination of two existing, commercial vermicomposting systems after two years of operation showed that earthworm density had increased only fourfold and this very poor level of earthworm production had serious implications for future commercial success.

vi) Until recently, large-scale vermicomposting systems operating in the UK tended to be relatively small. Typical size of bed area was 1,000 to 2,000 m^2 processing hundreds of tonnes of waste per year. With the development of much larger systems of the order of 10,000 m^2 of bed area, the waste processing capacity becomes thousands of tonnes and this compares with some smaller municipal composting facilities which need to conform to Environment Agency regulations. In particular, vermicomposting systems do not have leachate collection facilities, whereas most centralised composting operations are required to install these. No research of note has been conducted into the environmental impact of large-scale vermicomposting systems. As a result, the Environment Agency whose role is to monitor and license waste processing facilities has no technical basis on which to evaluate vermicomposting operations and very little understanding of their operation.

vii) There is no trade association or network that represents the vermicomposting or worm farming industry and which can assist in the provision of objective commercial information and research support. The vermicomposting industry is very fragmented with no means of promoting the development of the sector as a whole, in the way that the Composting Association represents the interests of large-scale composters and the Community Composting Network represents community interests.

5. 2 Aims of the project

Given the findings above there was clearly a need to generate objective information relating to both the technical and financial operation of large-scale vermicomposting systems. Two research programmes were initiated:

- An extensive technical programme of monitoring the performance, enhancement and environmental impact of experimental vermicomposting beds
- A research project which examined the financial and commercial aspects of large-scale vermicomposting.

Research Aims

- To design and install an experimental outdoor vermicomposting system, which facilitated the research programme and which incorporated design improvements compared with typical commercial systems.
- To monitor and evaluate the technical performance of the outdoor vermicomposting system.
- To investigate one simple method of enhancing the performance of an outdoor vermicomposting system, such as installing bed heating.
- To monitor and evaluate the technical performance of the outdoor vermicomposting system with bed heating.
- To monitor and evaluate the environmental impact of outdoor vermicomposting systems.
- To investigate realistic methods of mechanising aspects of the vermicomposting process, with particular regard to applying waste to the vermicomposting beds.
- To evaluate the cost-effectiveness and market potential of outdoor vermicomposting systems, with particular regard to basing the study on new technical knowledge gained and practical techniques developed during the course of the project.

6. Technical research

6.1 Technical research objectives

- To determine the rate of waste processing (kg/m^2 of bed/day) and vermicompost production over a period of 12 months for a processing system operating under normal weather and temperature conditions.
- To monitor the changes in earthworm population over a period of 12 months in order to determine potential rates of earthworm production for a processing system operating under normal weather and temperature conditions.
- To determine the time taken to full operation by monitoring the development of earthworm populations from a starter culture of 1 kg earthworms /m^2 of bed to establishment of working populations.
- To determine the effect of different starter culture densities (0.5 and 2.0 kg earthworms /m^2 of bed) on the time taken to full operation.
- To evaluate the quality of any vermicompost produced and to compare the characteristics of vermicompost to the Composting Association's National Compost Standard.
- To monitor continuously normal bed and air temperatures over a period of 12 months.
- To install a controllable method of bed heating and investigate the extent to which bed temperature can be regulated.
- To investigate the effect of minimal bed heating on earthworm populations and waste processing rate and compare this with the unheated beds operating under normal weather and temperature conditions.
- To investigate the environmental impact of the vermicomposting operation in particular in relation to the quantity and quality of leachate produced and the emission of greenhouse gases.
- To investigate mechanical methods of applying waste to the earthworm processing beds.

6.2 Experimental vermicomposting operation and research methodology

The technical research carried out as part of the vermicomposting project began with a 6 month setting up and bed construction period followed by a 12 month monitoring and experimental period. Details of the experimental trials that were undertaken can be found in the next section.

The setting up period was used to construct and commission eight individual experimental blocks of beds. The eight blocks of beds were each sub-divided into 5 individual beds. The blocks of beds were constructed out of breeze blocks with a damp-proof course membrane protruding (5 cm) out from the breeze block at the top of the beds to help prevent earthworm migration. Each individual bed was 1.5 metres wide by 6.6 metres long and beds were around 1 metre deep as shown in Figure 6. The dimensions of each Block were 1.5m wide by 25m long. Total bed area available for research was 400 m^2. Each bed was filled with composted horse manure/wood shavings bedding material (approximately 0.5 m deep) to contain the earthworm populations.

Figure 6
Bed design

Each block contained a leachate drainage and collection system, which allowed the environmental impact of leachate from the operation to be assessed. Leachate from each bed was allowed to collect in a separate holding (200 litres) for sampling (see Figure 7), before being pumped into a central collection tank (1500 litres).

Beds were unheated apart from one complete block of five beds which was heated (Block 5). Accurately controlled temperatures for each bed were achieved using individual electric heating cables and thermostats located in the bedding material. Thermocouples and data loggers continuously recorded bed and air temperatures to ensure that composting rates and earthworm populations were linked to prevailing environmental conditions. The location of each probe in the selected beds are shown in Appendix 1 and illustrated in Figure 8. No rainfall measurements were taken at the experimental site because of the close location of the Environment Agency rainfall monitoring site at Hook, which was 2 miles away.

Figure 7
Installation of a leachate holding tank

Figure 8
Probes measuring air temperature

After five months construction, the beds and surrounding infrastructure had been completed and starter cultures of earthworms were then introduced into the vermicomposting beds to allow them to acclimatise. The inoculation of beds with starter earthworm cultures of *Dendrobaena veneta* was carried out in late December 2000. The mean individual weight of earthworms was approximately 0.8g. The 12 month monitoring/experimental period commenced on 1st January 2001. The amounts of earthworms introduced into each bed and other experimental details can be found in the following sections.

The waste used as feed material for the earthworms during the vermicomposting trials was locally produced potato waste, which is a highly putrescible and very wet by-product of the food processing industry. Preliminary studies established that the potato slurry used as feed for the earthworms supported good levels of growth and was not toxic to earthworms. Regular deliveries of potato slurry were made to the experimental site in approximately 20 tonne batches and around 100 tonnes in total was used during the research study.

An important part of the overall research programme was to investigate the design and operation of a mechanised method of applying the potato slurry to the beds. Various designs were considered and a prototype mechanical feeder was constructed and tested by WRC staff (Figure 9).

Figure 9
Prototype mechanical waste feeder being tested

The prototype mechanical feeder was designed to straddle the worm beds while applying waste in the form of slurry, such that the waste did not cover the entire bed area. Applying waste in strips was considered important as a result of preliminary trials. These had suggested that total saturation of the bed area may reduce oxygen levels in the bedding material, creating hostile conditions for the earthworms.

The feeder needed to be designed and constructed on-site as no suitable commercial machine was available. A high ground clearance crop sprayer that had no further use, was found to fit the criteria. Modifications to the adapted machine were made throughout the project as problems became apparent. The footprint of the beds was designed to accommodate the machine so that a semi-automated system could be used. The waste handling and application process involved waste sludge being delivered in a tanker before being pumped into a holding tank. The waste was then transferred via a pump into the feed tank at the back of the feeder machine and then fed via small pipes into strips on the bed (see Figures 10 and 11).

Figure 10
Application of potato waste slurry to beds in strips

Figure 11
Lines of potato slurry applied to beds

The earthworm populations in each of the six main experimental blocks (Blocks 1-6) were monitored every 8 weeks, using a rigorous bed sampling regime. The time taken to sample all six blocks (30 beds) and to record the earthworm population data was typically five to six working days but the process took around 20 person-days to complete. Each 10 m^2 bed in each block was randomly sampled using a quadrate or sampling frame (area 0.24 m^2) and all bedding and earthworms/hatchlings/cocoons falling within the quadrate were removed and taken indoors to be counted and weighed were appropriate. See Figure 12 for an illustration of the bed sampling procedure.

Figure 12
Bed sampling procedure and sampling frame

The categories used to determine earthworm population profiles were defined as mature earthworms (sexually mature as shown by the presence of a clitellum or “saddle”) and immature earthworms, which were all other sizes except for the very small recently produced hatchling earthworms. Mature and immature earthworms were individually counted and weighed. Hatchling earthworms and cocoons were separately collected and counted.

Leachate samples were taken for analysis from all experimental blocks every eight weeks at least. Greenhouse gas emissions from selected beds were taken throughout the year using static chambers to sample surface fluxes (Figure 13) and syringes were also used to sample gases in the bedding material. The most rigorous sampling was performed in November 2001 and February 2002.

Figure 13
Static gas chambers used to determine fluxes

Technical research programme

Eight blocks of beds were available for the technical research programme. Blocks 1 – 6 were selected for detailed investigation of the overall performance of unheated and heated beds in normal operation. Block 7 was selected to undertake trials more focused directly on waste processing. Block 8 was scheduled for mechanisation trials.

Notes

Block 7 was selected to undertake trials more focused directly on waste processing. The original intention was to use mixed vegetable waste from a source segregation trial linked with a supermarket. The trial began in February 2001 and mixed vegetable waste was brought to the WRC site for processing. Unfortunately after two months this trial had to be abandoned due to the “foot and mouth” outbreak, making transport of waste to farms difficult. Due to the severity and duration of the “foot and mouth” epidemic, it was not possible to re-establish the mixed vegetable processing trial in the time available to the project. A smaller trial using mixed vegetable waste from various sources was begun in July 2001 but this is not reported here.

Also in July 2001, a much larger vermicomposting trial was commenced using potato slurry. Beds in Block 7 were inoculated with various earthworm starter densities (2, 3, 4, 5 and 6 kg per m^2 of bed) with the intention of determining the maximum waste-processing rate that could be achieved in relation to earthworm population. Unfortunately, this experiment was terminated when bed sampling confirmed that earthworms had been migrating from the high-density beds.

Experimental lay out and details

- Block 1 – Unheated beds

Stocking density of earthworms 1 kg per m^2 of bed
Waste application rate - on demand

- Block 2 – Unheated beds

Stocking density of earthworms 2 kg per m^2 of bed
Waste application rate - on demand

- Block 3 – Unheated beds

Stocking density of earthworms 1 kg per m^2 of bed
Waste application rate - on demand

- Block 4 – Unheated beds

Stocking density of earthworms 1 kg per m^2 of bed
Waste application rate – Twice Block 3 application rate

- Block 5 – Heated beds

Stocking density of earthworms 1 kg per m^2 of bed
Waste application rate - on demand

- Block 6 – Unheated beds

Stocking density of earthworms 0.5 kg per m^2 of bed
Waste application rate - on demand

- Block 7 – Unheated beds

Stocking density of earthworms:
Each bed was stocked at different densities 2, 3, 4, 5 and 6 kg per m^2 of bed
Waste application rate - on demand

- Block 8 – Unheated beds

Mechanisation Trials

7. Technical results

7.1. Monitoring and regulating bed temperature

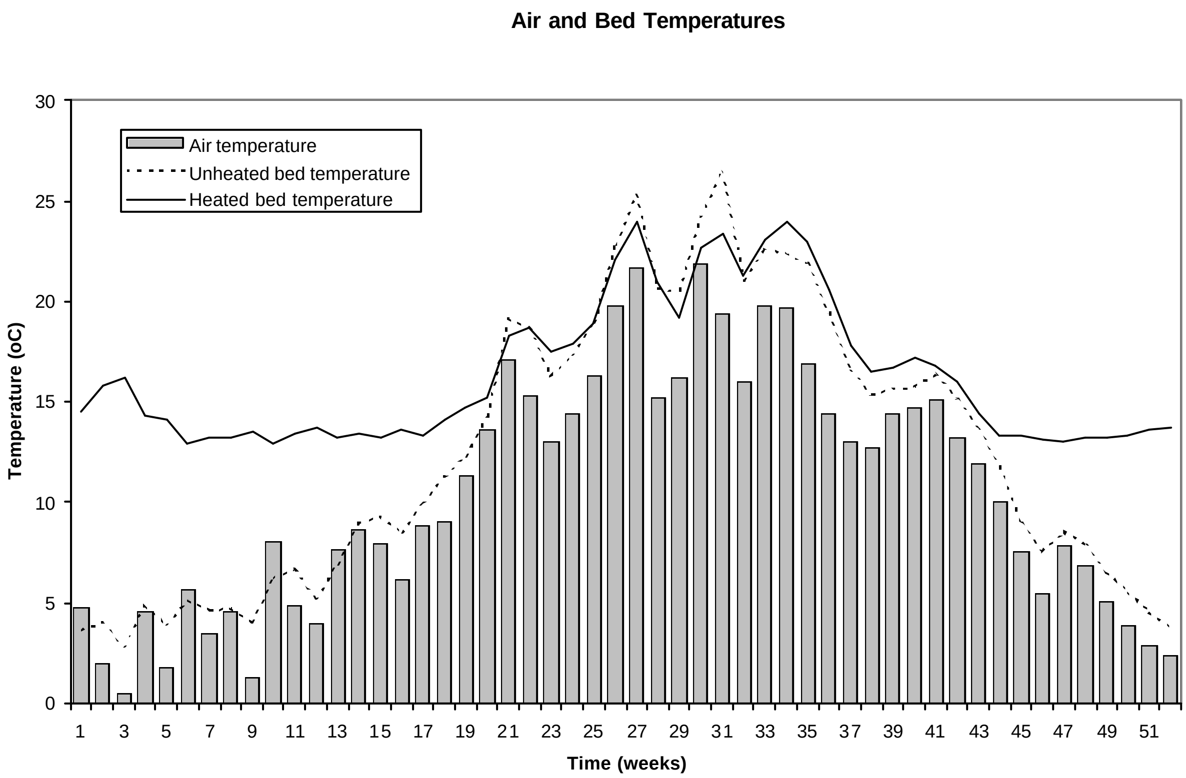
There were four temperature probes continuously measuring air temperature. It can be seen from Figure 14 that mean weekly air temperature directly over the experimental beds varied over the year from a low of approximately 1 °C in week 3 to a high of around 22 °C in week 28. The mean weekly temperature is calculated by averaging 24 daily recordings of temperature taken every hour, and then using the daily figures to calculate an average weekly temperature. It should be noted that the average figures include night and day time temperatures and actual minimum and maximum temperatures experienced can differ significantly from the average figure. For example, although the average weekly temperature in week 3 (week beginning 14th January 2001) was around 1 °C, the minimum temperature recorded that week was – 6.5 °C and the maximum temperature recorded that week was 7.1 °C.

As expected, the average temperature of the unheated vermicomposting beds reflected the air temperature very closely during the winter months. However, while the minimum air temperature during the winter months was often less than 0 °C, the temperature in the core of vermicomposting beds never dropped below freezing. For example, while the minimum temperature recorded in week 3 was –6.5 °C, the minimum temperature in the beds was 2.4 °C.

From an analysis of Figure 14, it appears that the bed temperatures in the summer months have the potential to rise to relatively high levels when air temperatures increase and this could have a detrimental effect on earthworm mortality. Although average temperatures in the centre of the beds tended to be around 20 to 25 °C for the hottest summer months, the maximum temperature recorded in the core of the beds was 32 °C. These temperatures have the potential to be harmful to the earthworms. Excessively high temperatures were recorded on the surface of beds directly under the cover sheeting and just below the food layer. Probe temperatures in excess of 48 °C were often recorded for the surfaces of beds and while these temperatures must be treated with some caution, due to direct sunshine affecting probe response, the surfaces of the beds often became very warm. These excessive temperatures would have had the effect of preventing earthworms from processing the waste feed for long periods and could have been harmful to the earthworms.

The attempt to provide minimal, controllable heating to the beds in Block 5 was very successful. The aim was to maintain the beds at an easily achievable temperature whenever the temperature was cold, with the use of thermostatically controlled heating cables. A maximum temperature of 15 °C was selected for various reasons. Firstly, to reflect the natural habitat for *Dendrobaena veneta* in Europe and secondly to study the vermicomposting process at the winter temperatures that could easily be achieved by housing vermicomposting operations in insulated polytunnels. Temperature records show that the average temperature for the heated beds, when the heating system was functioning, was 13.8 °C. This was for the first 20 weeks of the year and also the final 10 weeks of the year and this can be clearly seen in Figure 10. During the same periods, the average temperature of the unheated beds was 7.2 °C and the combined 30 week period represents around 60% of the year. The amount of electricity used by the heating cables was 5,000 units (5 months November to March), 500 units (April, May, September and October) and 0 units (June, July and August). During the summer months, the temperatures in both the heated and unheated blocks reflected air temperature and the heated block also experienced similar high summer bed temperatures to the unheated block, as described earlier.

Figure 14
Mean weekly air and bed temperatures

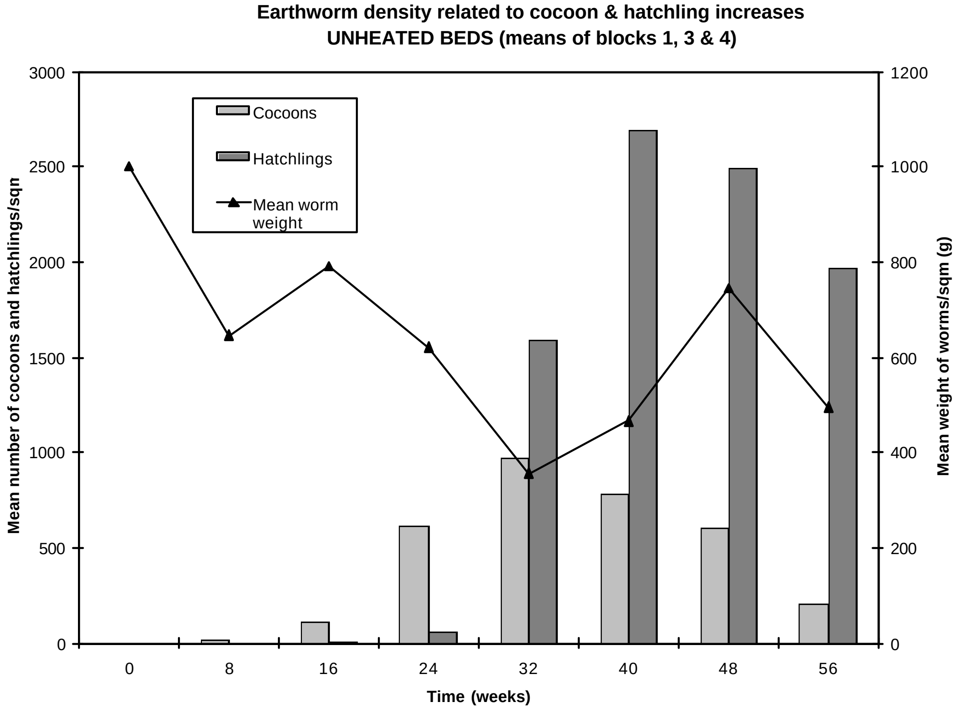


7.2. Earthworm populations and production

Earthworm populations and production from unheated beds

Figure 15 shows the changes in earthworm population for the unheated beds, which were inoculated with an earthworm starter culture density of 1 kg per m^2 of bed in late December 2000. This shows the combined results for three unheated

Figure 15
Earthworm population changes in the unheated beds



blocks of beds with this starter culture density (i.e. 15 individual beds). Comparable results for similar but heated beds can be found in Figure 16 on page 46.

For the unheated beds, it can be seen that the total weight of earthworms per m^2 of bed declined steadily for the first half of the research period. It is not clear why this happened but earthworm mortality is known to be relatively high in many hostile situations and it was also clear that a proportion of earthworms were migrating out of the beds in the unheated blocks.

It is likely that the low weight of earthworms per m^2 of bed found for the first sampling period, after eight weeks, was the result of sampling error. This is because many of the recently introduced earthworms were still found to be congregated in tight balls, in the manner of introduction and had not evenly dispersed around the beds. This made early bed sampling very difficult during the early stages of the project.

Some cocoons (spherical objects containing earthworm eggs) were first noted after eight weeks during the first sampling period. Very few cocoons would have been expected at this stage because the immature earthworms, inoculated into the beds in mid December 2000, would have had to grow to sexual full maturity before they were capable of producing cocoons. When the starter culture was first put into the beds, no earthworms were sexually mature, after eight weeks, around 60% were mature. After a further eight weeks, approximately 70% were mature and the mean weight of individual earthworms had increased from 0.8g to 0.97g. As expected, an increased number of cocoons were found during the second sampling period after 16 weeks, in late March. During the third sampling period some hatchling earthworms were evident and these had clearly emerged from the cocoons produced during the first eight weeks since introduction. This is very typical of cocoon hatching rates in cold conditions and published research findings confirm that hatching times can vary from 6 weeks to 18 weeks, depending on prevailing conditions.

It was not until 32 weeks after first introduction (July 2001) that large numbers of hatchling earthworms were present in the unheated beds (approximately 1,500 in number per m^2 of bed). During this period it was also clear that a proportion of the hatchling earthworms found in the previous sampling period had grown sufficiently to be defined as immature earthworms and to be included in the sampling statistics for mature and immature earthworms. This is shown by the increase in the proportion of immature earthworms in the beds, which increased from 30% in May to 50% in July.

For the 16 week period from July until the November sampling, the numbers of cocoons and hatchling earthworms produced appeared to increase in line with expectations and the density of hatchlings exceeded 2,500 per m^2 of bed. The number of earthworms defined as mature and immature also doubled in number during this period and this would be expected as more of the hatchlings grew into immature earthworms. The proportion of immature to mature earthworms rose to 80% as a result of the hatchlings gaining weight and being defined as immature.

In November 2001, the earthworm populations in the unheated beds seemed to be developing well. With the onset of cold winter conditions greatly reducing earthworm activity, feeding, growth and reproduction, it was expected that in February 2002 (the final sampling period) a similar population profile to November would have been found. To a large extent this was the case for the number of cocoons and hatchlings but the weight of mature and immature earthworms showed a significant reduction from around 0.75 to 0.5 kg per m^2 of bed and the proportion of immature earthworms increased from 80% to 86%. It is not clear why this occurred but the decline in earthworm numbers reflected a similar decline over winter at the start of the project. The mean weight of individual earthworms at the end of the project was around 0.4g and the proportion of mature, marketable earthworms was 14%.

In summary, the unheated beds after 13 months in operation seemed to perform relatively poorly in terms of producing earthworms. The initial starter culture of earthworms that were introduced into the beds declined to less than half its original weight within six months. This clearly had the effect of greatly reducing the number of cocoons and hatchlings that could be produced form the system. However, the starter culture of earthworms did reproduce but the study highlighted that at low temperatures it can take a long time to complete the earthworm's life cycle. In this case it took around 32 weeks to produce the first batch of immature earthworms during the cold winter months. Research suggests that this long period would be expected at very low bed temperatures. In a laboratory study, Viljoen et al (1992) found that the life-cycle of *Dendrobaena veneta* took five months to complete at a constant 15 °C and just over three months at 25 °C.

Future estimates

At the end of the one year study period, the earthworm biomass in the beds was still a lot less than the original starter culture biomass. Clearly, harvesting of mature earthworms would not be recommended in this case. However, it could be said that the beds were in a good position to develop over the next 12 months. When the beds were first inoculated with earthworms, the starter culture comprised 1 kg or approximately 1,200 sub-adult earthworms per m^2 of bed. At the end of 13 months, the beds contained around 0.5 kg of mainly newly produced earthworms, with an average individual weight of 0.4g. Hence, the number of earthworms at the start of the project was similar to the number at the end.

More importantly, the beds contained an average of 2,000 hatchlings per m^2 of bed which have the potential to grow into a further 2 kg of adult earthworms per m^2 of bed in around three or four months. It is almost impossible to speculate on future earthworm production from large-scale systems. However, if all of the hatchling earthworms became adult earthworms, after two years of operation it may be possible for the unheated beds to contain around 2.5 kg earthworms per m^2 of bed and around 5,000 cocoons and 5,000 hatchlings per m^2 of bed. It is likely that no more than 15 % of the earthworms in the beds will be mature and immediately marketable when harvested. In terms of medium term harvesting rates, it is clear that the low temperatures in the beds experienced for most of the year have a negative effect on the life cycle of the earthworms. It is unlikely that more than two earthworm life cycles could be completed during the year and this suggests that only around 0.75 kg of mature (larger than 1g) earthworms could be harvested per m^2 of bed per year.

It is clear that this design of open air bed system can suffer from periodic, rapid and severe declines in earthworm numbers. Moreover, observation of the beds confirms that there is a small but continuous natural drain of earthworms from the beds. Unless these factors are addressed, it is highly unlikely that earthworm biomass and the numbers of off-spring could be increased significantly in subsequent years.

Comparison with beds containing twice the earthworm starter density

Tables 2 and 3 show the development of earthworm populations for the three Blocks with starter densities of 1 kg per m^2 of bed. Also presented are Blocks 2 and 6, which were inoculated with double this density (2 kg per m^2) and half this density (0.5 kg per m^2) respectively. The experiment in Block 6 was ceased after week 32 when it became clear that the beds were being invaded by earthworms from a recently commenced vermicomposting experiment in Block 7.

Table 2
Earthworm biomass from starter cultures 1 kg, 2 kg and 0.5 per m^2 of bed

Time (weeks)	Earthworm biomass (g) Mean of (Blocks 1,3,4) (1kg per m^2)	Earthworm biomass (g) (Block 2) (2 kg per m^2)	Earthworm biomass (g) (Block 6) (0.5 kg per m^2)
0	1000	2000	500
8	646	1758	595
16	791	1812	476
24	621	1734	715
32	357	958	534
40	466	1130	1031
48	746	1300	Experiment ceased
56	495	1064	

One notable feature is that Block 2, with twice the starter density of Blocks 1, 3, and 4, suffered a marked decline in earthworm numbers during the first six months and earthworm numbers decreased to only 50% of its initial starter culture. This is a very similar trend compared with Blocks 1, 3, and 4. However for Block 6, starting half the density of earthworms of Blocks 1, 3, and 4, there was no decrease in earthworm numbers over the first six months, suggesting that a population of around 0.5 kg earthworms per m^2 of bed could be sustained by the bed system.

The numbers of cocoons and hatchlings that were produced by all Blocks, regardless of starter density, were broadly comparable. The earthworm populations in Blocks 1, 3, and 4 were actually similar to Block 6 but the populations in these beds were around half of the populations in Block 2. The results suggest that for Block 2, the number of cocoons and hatchlings that were produced per adult earthworm was only around half of the number achieved for the less densely populated blocks. This is very typical even at these relatively low earthworm densities and reproduction rate halving with a doubling of earthworm density is well documented.

Table 3
Cocoons and hatchlings from starter cultures 1 kg, 2 kg and 0.5 per m^2 of bed

Time (week)	Cocoon numbers Mean of (Blocks 1,3,4) (1kg per m^2)	Cocoon numbers (Block 2) (2 kg per m^2)	Cocoon Numbers (Block 6) (0.5 kg per m^2)	Hatchling numbers Mean of (Blocks 1,3,4) (1kg per m^2)	Hatchling numbers (Block 2) (2 kg per m^2)	Hatchling numbers (Block 6) (0.5 kg per m^2)
0	0	0	0	0	0	0
8	19	24	0	0	0	0
16	109	336	137	4	28	74
24	609	764	587	57	41	41
32	969	815	1915	1586	643	2574
40	779	1004	809	2687	2744	2884
48	607	557	Experiment ceased	2489	3612	Experiment ceased
56	202	390		1965	1624	

Conclusions

The performance of the unheated beds in blocks 1, 2, 3, and 4, which had earthworm starting densities of 1 - 2 kg per m^2 of bed, in terms of maintaining initial populations and producing earthworms was poor during the study period. Block 6, which had a lower starting density of 0.5 kg per m^2 of bed, seemed to perform slightly better in the sense that its initial population of earthworms was able to be sustained. It also produced comparable numbers of cocoons and hatchlings to the beds with larger starting densities. Unfortunately, this experiment was terminated part way through the year due to ingress of earthworms from another recently started trial.

Continuous temperature monitoring showed the bed temperature to be very low (mean 7.2 °C) for around 60% of the year. The earthworm species used in the project, *Dendrobaena veneta,* are known to grow and reproduce optimally at temperatures between 15 – 25 °C and it could be predicted that little population development would occur at very low temperatures. Over the first six months of the study, the initial earthworm populations in most of the unheated beds were reduced to 50% and despite new earthworms being produced during the latter stages of the research, the populations tended to remain at low levels. As well as low temperatures reducing the potential production of earthworms, it appears that earthworms were able to migrate from the beds and this is a common problem with outdoor bed designs.

In conclusion, it would seem that the unheated bed system was capable of producing a reasonable number of cocoons and hatchlings. The presence of these should ensure that after two years the beds should be capable of supporting a low density of earthworms (around 2.5 kg earthworms per m^2 of bed). This would be adequate for processing a limited amount of waste and could produce some earthworms for harvesting in the longer term. The unheated experimental beds at WRC appeared to perform comparably with other outdoor vermicomposting systems investigated (Appendix 2) but in general the method investigated at WRC performed poorly in terms of the claims made by commercial suppliers of outdoor vermicomposting systems.

Earthworm populations and production from heated beds

Temperature records show that the winter/spring/autumn temperatures for the unheated beds was 7.2 °C for a 30 week winter period, representing around 60% of the year. Published research clearly shows that the best earthworm growth and reproduction is achieved by maintaining temperatures in the range 20 °C to 25 °C. While these optimum temperatures can be clearly achieved over the summer months for outdoor vermicomposting beds, winter/spring/autumn temperatures in the UK are very low. Consequently, maintaining acceptable levels of earthworm activity during most of the year is almost impossible without some form of background heating.

By using a simple thermostatically controlled electric cable heating system to boost temperatures during the coldest months it was possible to increase the average temperature for the same 30 week period to 13.8 °C. The purpose of this study was to assess the effect of minimally increasing bed temperatures on earthworm populations and earthworm output compared with the unheated beds.

Figure 16 shows the changes in earthworm population over the research period of 56 weeks during which time earthworm populations in the heated beds (Block 5) were monitored. In the same way as the unheated beds, the heated beds were originally inoculated with sub-adult earthworms only, at a density of 1kg earthworms per m^2 of bed. The mean individual weight of earthworms inoculated into Block 5 was approximately 0.8g. The earthworm populations in Block 5 were monitored every 8 weeks as for the other unheated blocks.

<u>Figure 14</u>
<u>Earthworm population changes in the heated beds</u>

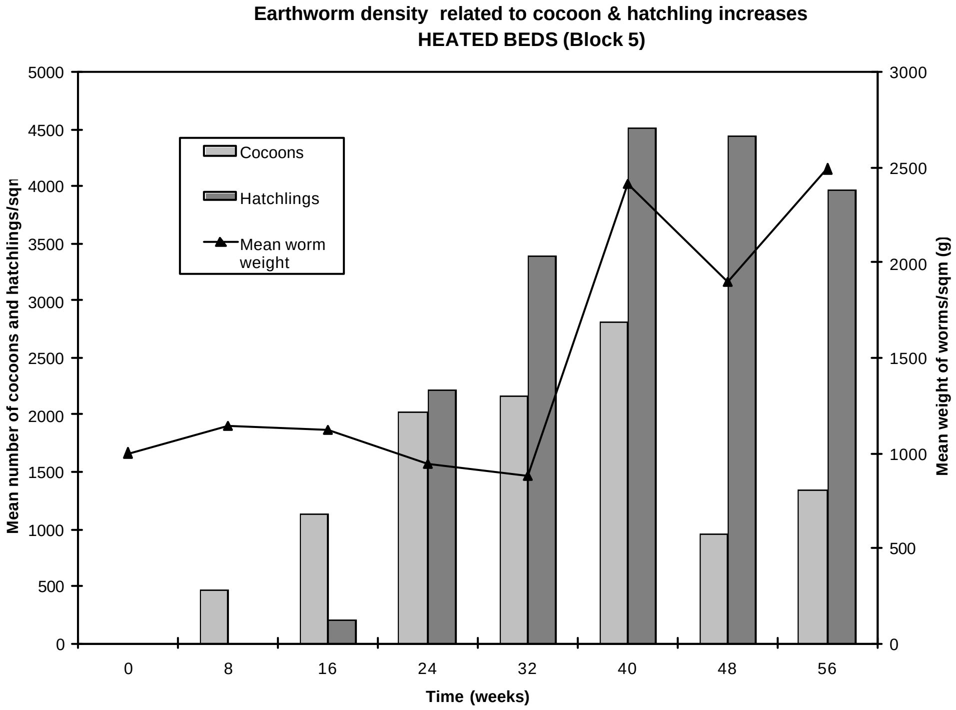


Figure 16 shows that for the five heated beds (Block 5) under study, the total weight of earthworms per m^2 of bed remained relatively static for the first half of the research period. This is in direct contrast to the results for the 15 unheated beds also being monitored, all of which experienced over 50% reduction in earthworm biomass, during the same period.

A significant number of cocoons were recorded after eight weeks during the first sampling period and 87% of earthworms were found to be mature compared with only 60% in the unheated block. After a further eight weeks, approximately 91% were mature and the mean weight of individual earthworms had increased from 0.8g to 1.02g. As expected some hatchling earthworms were evident during the second sampling period after 16 weeks, in late March. The first hatchlings were not detected until 24 weeks had elapsed for the unheated beds. After 24 weeks (late May) the numbers of cocoons and hatchlings recorded for the heated beds were 2,000 and 2,200 per m^2 of bed respectively and for the unheated beds the equivalent numbers were 600 and 60 per m^2 of bed. Although the total weight of earthworms in the unheated beds was by then only two thirds of the population in the heated beds, clearly the effect of the bed heating during the cold months was very pronounced in terms of greatly enhancing earthworm reproduction.

During the warmer summer months, shown by results for weeks 32 and 40, the cocoon and hatchling production from the unheated beds greatly increased.

However, total numbers of cocoons and hatchlings remained much greater in the heated beds due to the accelerated production in earlier months. Also for week 40, the first significant increases in earthworm population for both heated and unheated beds were noted. This was the result of a significant proportion of hatchlings gaining weight, becoming immature earthworms and being included in the earthworm weight and number statistics. For the unheated beds from sampling week 32 to week 40, the earthworm density increased slightly in the eight-week period. However, earthworm biomass more than doubled for the heated beds as a result of the large production of immature earthworms from hatchlings.

From Figure 15 showing results for the unheated beds it can be seen that earthworm numbers and biomass continued to increase into the next sampling period (week 48). This was expected since temperatures in late September and early October were reasonably mild for autumn. It was also expected that the earthworm biomass in the heated beds would have increased to at least 4 kg per m^2 of bed, mainly as a result of the development of more immature earthworms from hatchlings. However, results for the heated bed in sampling week 48 showed that earthworm biomass had decreased significantly during the eight-week period.

Figure 17
Mass Migration of Earthworms

This was undoubtedly due to mass migration of earthworms from the heated beds, which occurred over the period 20th to 22nd October 2001. Please refer to Figure 17. Migration of earthworms from other beds also occurred. The migration period was the fourth wettest three-day period over the course of the year with around 27 mm of rain falling (over an inch of rain). This significant rainfall event, following the two wettest months of the year, also coincided with the beds being applied with potato slurry. It is highly likely that water-logging in the beds combined with the presence of highly putrescible material being washed into beds would have greatly lowered oxygen levels creating very hostile conditions in the beds for the earthworms. In addition, the earthworms in the heated beds were at their maximum density during the research study and it is not surprising that many migrated from the beds to escape the hostile conditions. Although it is not possible to be precise about the cause of the periodic migrations, it is known that so-called *epigeic* species of earthworms, such as the particular species used in these trials, are prone to migrate and this is normal behaviour. This grouping of species, are normally litter dwelling and are categorised as ecological type "r" which means that they are selected to be comparatively mobile and to search on the surface for food or shelter. Other earthworm species normally have a low capacity to migrate (K selected).

Despite the presence of an extended lip on top of the beds which was installed to help prevent migration, large numbers earthworms were seen migrating from all beds at night. It is not possible to calculate the exact number of earthworms that migrated from the heated beds but it is likely that the earthworm biomass present in the heated beds in mid October would have been at least 3 kg per m^2 of bed. Since the density of earthworms in sampling week 48 was only around 2 kg per m^2 of bed, it is likely at least 1kg earthworms per m^2 of bed were lost and it is possible that it was much more than this. Overall, therefore, it is possible that at least one third of all adult earthworms in the heated beds migrated out of the beds during this period and this amounts to around 50kg from Block 5.

Figure 16 shows that the final density of earthworms in the heated beds at the end of the project (week 56) had begun to increase again after the mass migration and the final density was 2.5 kg earthworms per m^2 of bed. The mean weight of individual earthworms was 0.47 g and on average, 25% of the earthworms were mature and would have been marketable.

Future estimates

At the end of 13 months, the beds contained around 2.5 kg of mainly newly produced earthworms. The beds also contained an average of 4,000 hatchlings per m^2 of bed which have the potential to grow into a further 4 kg of adult earthworms per m^2 of bed in around three months. There were also 1,300 cocoons per m^2 of bed. Furthermore, on the basis of reproduction data, the heated beds were predicted to produce earthworm densities of approximately 4 kg per m^2 of bed by November, but the mass migration of around one third of the earthworm population out of the beds proved to be a significant setback.

Clearly the heated beds have the potential to support a working earthworm density of at least 4 kg per m^2 of bed and the rate of development suggests that this could be achieved after one year. This will only be achieved if earthworms are contained within the beds and migration prevented. However, there is also a need to prevent beds from becoming waterlogged and to prevent the creation of hostile bed conditions for the earthworm populations, otherwise high mortality will replace high migration. From the research conducted during this phase it is not possible to estimate the maximum carrying capacity (maximum earthworm density) that the heated earthworm beds might achieve. However, a working density of 4 kg per m^2 of bed should be easily achievable and this should be sufficient for cost-effective processing of waste.

The amount of mature earthworms (weighing in excess of 1 g) per year that could harvested from the system while still retaining a high working density is more difficult to estimate. Maintaining earthworm populations at high densities is known to greatly reduce reproduction rates. In terms of medium term harvesting rates, it is clear that the increased winter temperatures in the heated beds, compared with the unheated beds, shortened the time required to complete the life cycle of the earthworms. However, with a heated bed temperature of 13.8 °C during winter, which was used in the current research programme, it is still unlikely that more than three earthworm life cycles could be completed during the year. If it is assumed that a working density of around 4 kg of earthworms per m^2 of bed is necessary to enable good waste processing rates to be achieved, it is estimated that around 3 kg of mature earthworms per m^2 of bed could be harvested, if manually collected regularly throughout the year. This also assumes that around 25% of the 4 kg would have been mature (i.e. larger than 1g). Clearly, more earthworms of smaller size could be harvested but this could significantly reduce the output from the system in the longer term.

Increasing the bed temperature to around 20 °C would certainly reduce the time taken to complete the earthworm's life cycle further and may result in higher earthworm densities in the beds and an increased proportion of mature specimens. All of these factors could greatly increase the amount of mature earthworms that could be harvested from the system. However, it is not clear that increasing bed temperature would be cost-effective and more research needs to be undertaken to investigate this.

Conclusions

Clearly heating the beds to an average winter temperature of around 14 °C for around 60% of the year has greatly increased earthworm densities in the processing beds, compared with not heating. The heated beds show the potential to support a working earthworm density of at least 4 kg per m^2 of bed and this could be achieved after one year. However, this will only be achieved if earthworms are contained within the beds and mass migration prevented. It has been estimated that a possible 3kg of mature earthworms per m^2 of bed could be collected per year from such a system, if regularly harvested. Increasing the bed temperature to around 20 °C over winter may increase the amount of mature earthworms that could be harvested from the system and could also result in increased waste processing rates. Research into the effectiveness of increasing bed temperature should be undertaken.

7.3. Waste characteristics and processing rates

The organic waste selected for this programme of research was obtained from a potato processing factory and is a by-product of potato chip manufacture. Although a waste product from the process, the waste potato slurry is normally sold as an animal feed. It was selected for this research for many reasons. Firstly, similar slurries and other very wet and highly putrescible food processing wastes have been used in much of the scientific earthworm research that has been published and such wastes are considered to be highly appropriate for vermicomposting. Secondly, potato slurry in terms of its chemical composition and physical characteristics is typical of many food wastes that are currently landfilled. It is also similar to many wastes being used by worm farmers (e.g. apple and other fruit pulps, brewery waste and processed vegetable waste). Also very importantly, the composition of the potato slurry was likely to be consistent and because its availability was guaranteed for the duration of the project. Section 7.6 gives details of the development of a machine that was used to apply the slurry to the beds. It can be seen from this section that the slurry was applied in thin bands over the beds and this method of application was specifically devised to allow maximum surface area of waste to be available to the earthworms when feeding. Monitoring of earthworm feeding patterns had previously identified that earthworms avoided areas of the beds directly below the waste, preferring instead to feed along the outsides of the lines of slurry. There is some evidence arising from the project that suggests that earthworms may have avoided these areas because bedding material directly below the waste was deficient in oxygen and also contained higher levels of soluble nutrients compared with other areas of the beds. This is consistent with concentrated liquid seeping out of the very wet slurry into the bedding below making these conditions less preferable to the earthworms.

Prior to the potato slurry being used in the research programme, its chemical and physical characteristics were determined and evaluated (Appendix 3). The potato slurry was also used in preliminary earthworm mortality and growth trials, which confirmed that it was a suitable waste feed material for earthworms and amenable to vermicomposting.

The potato waste when delivered to site by tanker (around 20 tonnes per load) was often fresh from the factory as shown by its elevated temperature. The slurry contained a mixture of steamed potato flesh in homogenised form and fine potato skins. In brief, the chemical analysis of the potato waste as delivered and when applied to the processing beds showed it to be very wet (around 10% solid material), relatively acidic (pH 3.7 – 4.8) and very rich in dissolved nutrients (electrical conductivity 8.2 mS/cm). Nutritionally and in terms of waste processing the potato slurry would be considered to be highly nutritious and very putrescible, with the solid material in the slurry having a relatively high protein content of approximately 20% (total nitrogen content x 6.25), a carbon to nitrogen ratio (C:N) of 15:1 and with most of the solid material being readily amenable to decomposition (high organic matter content 88%).

Waste Processing Rates

Tables 4 and 5 show the amounts of potato waste applied to the experimental Blocks over the whole 12 month research period and secondly, during the latter stages of the project when the processing beds should have become established and earthworm populations developed. Table 5, showing the amounts applied from August to December is probably the more significant table and indicates that the beds were converting between 0.9 to 1.2 kg potato waste / m^2 / day over the summer / autumn / winter period. It should be noted, however, that not all the potato waste that was applied to Blocks 1 and 3 was processed into vermicompost, since a significant fraction of waste typically dried out due to slow processing by the earthworm populations and became impossible to process further. This was removed but reject weights were not recorded. All of the waste in Block 5 was converted into vermicompost. The waste was applied to the beds “on demand” in the sense that waste was only applied to the beds when all or most of previous waste application had been processed by earthworms.

Table 4
Amounts of potato waste processed (over 12 month period)

	Block 1	**Block 3**	**Block 5**
Total amount of potato waste applied (kg)	1200	1200	1600
Amount processed per m^2 of bed per day (kg/ m^2 /day)	0.7	0.7	0.9

Table 5
Amounts of potato waste processed (5 month period from 1 August to 31 December)

	Block 1	**Block 3**	**Block 5**
Total amount of potato waste applied (kg)	650	650	900
Amount processed per m^2 of bed per day (kg/m^2/day)	0.9	0.9	1.2

Section 7.2 (earthworm population section) shows the weight of mature and juvenile earthworms in Blocks 1 and 3 during the period August to December and the number of hatchling earthworms. The weight of mature and juvenile earthworms varied between 0.4 to 0.7 kg per m^2 of bed plus there were on average, approximately 2,000 hatchling earthworms per m^2 present in each processing bed. Hatchling earthworms typically weighed 0.1g each giving a total weight of hatchlings of around 0.2 kg per m^2 of bed. Therefore the total weight of earthworms in Blocks 1 and 3 varied between 0.6 and 0.9 kg per m^2 of bed during the time a maximum of 0.9 kg per m^2 of bed of potato waste was processed. Not all the potato waste was processed by the earthworms and some was removed from the beds.

For the heated block (Block 5) the weight of mature and juvenile earthworms varied between 1.0 kg to 2.5 kg per m^2 of bed plus there were on average, approximately 4,000 hatchling earthworms per m^2 present in each processing bed giving a total weight of hatchlings of around 0.4 kg per m^2 of bed. Therefore the total weight of earthworms in Blocks 1 and 3 varied between 1.4 and 2.9 kg per m^2 of bed during the time when a maximum of 1.2 kg per m^2 of bed of potato waste was processed. All the potato waste was processed by the earthworms during this time.

The maximum waste processing rates obtained during this research study were from the heated beds, with the highest population of earthworms. Since earthworm populations were still developing rapidly during the year, it is difficult to equate waste processing rates with earthworm density. However, for the second half of the project when the beds had become established, it would appear that around 2 kg of earthworms per m^2 of bed in the heated beds processed approximately 1.2 kg per m^2 of bed of potato slurry. This is equivalent to 0.6 kg of waste processed by 1 kg of earthworms. Research undertaken on biosolids (sewage sludge), with similar physical and chemical properties to potato sludge, suggests that a processing rate within the range 0.8 to 2.0 kg of waste per kg of earthworms per day should be achievable given suitable processing conditions. It is likely that sub-optimal processing conditions (e.g. low bed temperatures) would result in processing rates towards the lower end of the range.

There is little doubt that more waste than the amounts given here could have been applied to the experimental beds. There are many reasons for lower than expected waste processing rates such as the need to follow a rigorous feeding regime of “feeding on demand”, which was needed to achieve accurate monitoring of application rates. This conclusion is supported by research published elsewhere which suggests that maximum earthworm biomass production is best achieved by “excess application” of waste to beds followed by rejection of unprocessed waste. Excess application is probably a sound strategy since this is likely to greatly reduce competition for available food. During this research programme, an experiment was specifically set up to investigate the effect on waste processing rates and earthworm output by doubling the waste application rate for Block 4, compared with Block 3. Unfortunately, while it was possible to apply the excess potato slurry relatively easily, the increased amount had the effect of smothering the surface of the beds. This in turn appeared to create hostile conditions for the earthworms in the Block 4 beds, leading to evidence of increased earthworm mortality. This, coupled with increasing amounts of rejected waste from the beds led to this experiment being abandoned after 12 weeks and feeding on demand was re-introduced.

It is also clear that upper bed temperatures in summer and early autumn were excessively high on many occasions due to solar gain. There was good observational evidence to suggest that this prevented earthworms from entering the potentially lethal upper zones for long periods of time and that the quality of the waste on the surface also suffered due to desiccation. Further published research has shown that frequent applications of fresh food in small amounts has been shown to result in increased earthworm biomass production, clearly indicating that nutritional value of waste decreases rapidly with time. Hence, rather than feeding on demand and applying waste to beds only when the previous batch has been processed, a more effective method might be to apply fresh waste little and often and accept the consequences of higher reject rates from unprocessed waste.

Waste processing rates could have been greatly reduced by any of the factors discussed above and continued research into developing enhanced methods of applying waste to beds is a clear priority.

7.4. Compost characteristics and production rates

There was no measurable increase in the amount (volume) of bedding material in the beds as a result of the addition of potato slurry over the period of 12 months. During the initial stages of vermicomposting, there was a clear reduction in the height of the bedding material in all beds as the material itself decomposed and slumped. Some additional bedding material was added to all beds, which was equivalent to the amount needed to ensure that the upper temperature probes were covered in bedding. It is assumed that any decrease in bedding volume due to natural decomposition was matched by the additional volume of earthworm casts formed from the vermicomposting of the potato slurry. Rather than the earthworm casts forming a defined layer on the surface of the bedding, casts were incorporated into the bedding material and the resulting compost (vermicompost) should be regarded as an intimate mix of earthworm casts and the original bedding material. The bulk density of the bedding material, initially placed in the beds, was 0.4 kg/litre while the final mix of bedding and casts (vermicompost) after 14 months was 0.6 kg/litre.

This is typical of vermicomposting operations where bedding material is provided initially to separate the earthworm population from potentially harmful waste and the hostile conditions in the processing beds arising from this. It is comparatively rare for earthworms to be added directly to the waste being vermicomposted. Often vermicomposting beds are not disturbed for up to five years and no attempt is made to remove earthworm casts from the bedding. Over a long period of time it can be seen that the proportion of the final compost which is derived from earthworm casts alone, should increase significantly. Over a period of many years, it may be possible for the earthworm cast layer to dominate the upper layers of the bedding to the extent that this could be removed relatively intact.

It was not possible in the relatively short experimental period of 12 months for any discrete earthworm cast layer to build up. One reason for this was that the waste being applied was highly putrescible and was readily consumed by earthworms and also decomposed very readily leaving very little residue on the bed surface. Appendix 4 shows how the chemical characteristics of the bedding material were changed over the 12 months through natural decomposition of the wood chip bedding and the application of potato slurry and the subsequent incorporation of the earthworm casts. It can be seen that the amount of soluble nutrients (water extractable nutrients) present in the bedding built up over time indicated by the increase in electrical conductivity and in particular as shown by increases in valuable plant growth nutrients potassium (K) and phosphate (PO_4). Importantly, the total amount of nitrogen present in the final vermicompost was over double the amount in the original bedding and there was also evidence of nitrate formation in the vermicompost, increasing its value as a plant growth medium. One negative aspect of the vermicompost, if used unamended as a plant growing medium, would be its relatively high pH (7.3). Growing plants prefer slightly acid conditions (pH less than 7) but since waste-derived compost is typically alkaline, this is not of great concern.

Summary of vermicompost characteristics related to TCA compost standard

The Composting Association (TCA) introduced a national standard for waste-derived compost in May 2000. Vermicomposts are not eligible for this standard since they are not derived from “material that has been subjected to controlled, self-heating biodegradation under aerobic conditions……”. However, it is useful to make some comparisons between the vermicompost produced during this research programme and the TCA standard. In particular, the TCA standard requires limit levels for selected Potentially Toxic Elements (PTEs) to which composts must adhere and also insists that other obligatory information is provided. It should be noted that the TCA standard requires composts producers to test other compost parameters. One of the most important of these is the test for human pathogens (Salmonella spp and E. coli) but since the vermicomposted potato slurry had previously been boiled, this test was not undertaken. The TCA plant tolerance test to determine phytoxicity involves extensive plant growth trials and this was beyond the scope of the vermicomposting research project.

The characteristics of the vermicompost produced during this programme is presented in Tables 6, 7 & 8 and Appendix 4. It can be seen from the tables that the vermicompost would fall easily within the TCA limits for potentially toxic elements (PTEs). This is not surprising since the bedding material used was shredded wood chips and the waste was derived from an original material which was intended for human consumption. If the bedding material had been derived from composted green waste and sewage sludge had been the waste material being vermicomposted, the resulting vermicompost may have fallen outside some of the PTE limits. Equally, because of its origins, the vermicompost tested was clearly very uncontaminated.

Table 6
TCA limits for PTEs compared with vermicompost

PTEs	Vermicompost (mg kg^{-1} dry matter)	TCA Upper Limit (mg kg^{-1} dry matter)
Cadmium (Cd)	1.1	1.5
Chromium (Cr)	4.4	100
Copper (Cu)	17.0	200
Lead (Pb)	Not detected	150
Mercury (Hg)	Not detected	1.0
Nickel (Ni)	5.4	50
Zinc (Zn)	6.5	400

Table 7
TCA limits for physical contaminants compared with vermicompost

Parameters	**Vermicompost**	**TCA Upper Limit**
Physical contaminants >2mm (glass, metal, plastics)	None detected	1% m/m of total air dried sample
Stones >2mm	None detected	1% m/m of total air dried sample
Weed contaminants (weed propagules)	None detected	5 viable weed propagules l^{-1}

Table 8 shows the important chemical characteristics of the vermicompost produced during the study. These are compared with typical characteristics of fine and coarse compost produced by large-scale composting operations in the UK, as tested by the Composting Association. The vermicompost, because it contains high levels of bulky bedding material, is probably more similar in

Table 8
Properties of vermicompost and composts produced in the UK

Source compost data: Biological techniques in solid waste management and land restoration. Published by CIWM (2002).

Property	Vermicompost	Typical Fine compost (less than 10 mm)	Typical Coarse compost (10 – 25 mm or unscreened)
Total Nitrogen (% dry wt)	1.78	1.0	1.4
Total Phosphorus (% dry wt)	1.66	0.2	0.2
Total Potassium (% dry wt)	0.86	0.5	0.5
pH	7.3	8.4	8.5
Electrical Conductivity (μS/cm)	462	715	592
C:N	25:1	12.6	12.1
Organic Matter (% dry wt)	80	26	28
NO_3 (mg/kg dry wt)	620.0	44.0	37.5
NH_4 (mg/kg dry wt)	0	12.0	2.0
Mg (mg/kg dry wt)	N/D	902	787
Bulk Density (kg/litre)	0.6	N/D	N/D

N/D = not determined

physical character to the typical coarse compost than the fine compost. Physical parameters of the vermicompost such as bulk density and air filled porosity were determined but not reported here. In particular it can be seen that the vermicompost is very rich in total nitrogen and soluble nitrate nitrogen (NO_3) compared with both grades of municipal compost and this is very typical. The level of total phosphorus is very high in the vermicompost, and this is probably due to high levels in the potato slurry. Organic matter and C:N ratio in the vermicompost are also high compared with the compost but these probably relate to the relatively undecomposed component of bedding material. From the chemical analyses alone it is not possible to evaluate how the vermicompost or any compost would perform when used to grow plants or act as a soil conditioner.

Any thorough evaluation of the vermicompost as a plant growth medium would involve an extensive bioassay using a variety of plant types. This was outside of the scope of the project. However, a cress seed bioassay test was performed on the leachate from each block, which was recently derived from the final vermicompost. This was undertaken to test if the level of soluble nutrients and dissolved organics in the vermicompost would harm plant material. A particular problem associated with vermicomposting is that it is a continuous processing system compared with the batch method of composting. Hence, fresh waste is applied in relatively small amounts to the surface of vermicomposting beds and this fresh material needs to fully decompose and the vermicompost left mature otherwise it may be phytotoxic (harmful) to plants. Appendix 4 shows the results from the cress seed bioassay test and these suggest that the vermicompost, while not completely safe to plants (Germination index = 100%), the Germination index was mostly above 60% and could be used, with caution, for growing plants. If used as a multipurpose compost for growing plants, the vermicompost would probably benefit from blending with a low nutrient acid material, such as coir, to reduce pH and electrical conductivity. This is also true for the municipal composts highlighted in Table 8. The vermicompost, by contrast, could be used perfectly safely as an excellent soil improver with very little amendment.

7.5. Environmental impact of the vermicomposting process

As with all waste processing operations, vermicomposting has the potential to cause pollution and it has therefore an environmental impact which needs to be evaluated. During the course of the research programme, the environmental impact of vermicomposting was investigated with respect to the leachate from the outdoor processing beds and in terms of greenhouse gas emissions (methane and nitrous oxide). Although studied extensively in regard to municipal composting operations, neither leachate production or greenhouse gas emissions from large-scale vermicomposting have been the focus of much research in the past.

Leachate

Since open air vermicomposting beds in the UK tend to be covered only by permeable sheeting, they allow rainfall to percolate through the waste applied to the surface of beds, earthworm casts and then through the bedding material. This process allows rainfall to dissolve and suspend organic material, which mixes with any liquid seepage coming from the waste itself thereby creating a leachate. This leachate in open air systems has the potential to percolate into the soil beneath beds and if water courses are close, pollution of these may occur. The research programme identified the lack of knowledge about leachate production from such systems and set up leachate collection facilities to enable data on leachate production and characteristics to be amassed.

Leachate arising from all of the six main blocks of experimental beds was separately collected in six separate holding tanks (200 litres capacity), which were sampled at least every eight weeks (mid month) for the final six months of the project. This was when the processing beds and the waste application regime had become established. The results of the various chemical analyses are presented in Appendix 5. When the holding tanks were full, the leachate in each tank was subsequently pumped into a central tank (1,500 litres capacity). It was not possible during the 12 month trial period to accurately measure the total volume of leachate collected during the year or the amounts collected from individual blocks of beds. However, accurate monthly rainfall measurements were available from the Environment Agency for the immediate area (Appendix 6) and from this, approximate volumes of leachate from the blocks can be estimated. Having an estimate of the volumes of leachate collected during each month, it is then possible to relate rainfall to leachate production, waste application rates and leachate characteristics.

It is known that 1mm of rain falling on 1 m^2 of bed will produce approximately 1 litre of leachate. For example, 25.4 mm of rainfall (i.e. one inch) falling on one block of beds (50 m^2 metres) will produce around 1270 litres of leachate. The rainfall data shows that in May 2001, 25.5 mm of rain fell in the area indicating that each block of beds would have produced around 1270 litres of leachate. Although, it should be noted that not all of the rain falling on the beds would result in leachate since some will be absorbed by the bedding material depending on prevailing temperature and weather conditions.

Table 9
Leachate characteristics

Month	Mean weight of potato waste applied to each Block (kg)	Rainfall (mm)	Maximum volume of leachate Produced per Block (litres)	Mean BOD all Blocks when sampled (mg/l)	Mean COD all Blocks when sampled (mg/l)	Mean Nitrate concentration all Blocks when sampled (mg/l)
July	150	23.6	1180	42	3304	61
Aug	150	86.2	4310	21	2180	242
Sept	150	75.8	3790	44	2203	157
Nov	150	32.7	1635	46	1727	287

Leachate Biological Oxygen Demand (BOD), Chemical Oxygen Demand (COD) and nitrate concentration are often used to indicate the leachate's potential to pollute watercourses. From Table 9 it can be seen that during the months studied, the BOD, COD and nitrate concentration of the leachate collected from each block of beds did not vary significantly. This would be expected, even though the rainfall varied from 23.6 mm to 86.2 mm per month, since the capacity of the holding tanks was small and relatively low rainfall (around 4 mm) would have been sufficient to fill the tanks. Hence, samples were always taken from full holding tanks and records show that these tanks had always been filled by leachate arising within the previous few days.

The leachate BOD was found to be consistently low during the project although COD was moderately high. This suggests that the leachate from the waste and earthworm casts was being treated by microbial action as it passed through the bedding and this material was therefore acting as a biofilter. A full set of leachate characteristics for each block of beds collected during the project is given in Appendix 5. For comparison, in Appendix 7, the characteristics of compost leachate are presented which were taken from two phases of windrow composting of green waste; the first six weeks and the second six weeks of composting. Points to note are that the leachate from the vermicomposting beds had low COD levels even compared with the latter stages of composting and its levels of BOD were consistently very low, confirming that vermicomposting leachate would be much less polluting. The electrical conductivity of vermicomposting leachate was also low compared with compost leachate, suggesting a much lower level of dissolved salts. Finally, the vermicomposting leachate contained much higher concentrations of nitrate and phosphorus and this suggests that it could have good fertilising properties if used undiluted in agriculture.

A cress seed bioassay test was performed on the leachate from each block (See Section 7.4). This concluded that the leachate, while not completely safe to plants (Germination index = 100%), the Germination index was mostly above 60% and could be used, with caution, for fertilising growing plants.

It may be concluded that the experimental vermicomposting system under study produced a significant volume of leachate during the course of the project. It is contended that the volume of leachate produced was related to rainfall and, in general, each m^2 of bed receiving 1 mm of rain would have produced approximately 1litre of leachate. However, while it would appear that the leachate had the potential to pollute, it was found to be less polluting compared with the leachate from composting sites. In one interesting respect the vermicomposting leachate was found have a consistently very low BOD, considerably reducing its polluting potential. On a positive note, it contained useful concentrations of plant nutrients making it useful as a liquid fertilising medium, if used with care. When the leachate was tested using a cress seed bioassay test it was found to inhibit seed germination and growth to some degree. Therefore, if used in horticulture as fertilising medium for sensitive plants, the leachate would need to be diluted to ensure minimal plant damage.

Greenhouse gas emissions

Selected blocks of earthworm processing beds were monitored for the emission of the greenhouse gases, methane and nitrous oxide for the final six months of the project. The selected blocks were 3, 5 (heated) and 6 and gaseous emissions were sampled from the surface of beds and from within the bedding material. Surface monitoring was carried out using standard, static chambers as shown in Figure 10. Gas fluxes on the surface were measured by placing chambers directly over the waste on the surface of the beds and also over the bedding. Gases were sampled from within the bedding material by using embedded tube samplers and by syringe.

Results for fluxes of methane and nitrous oxide from surface measurements only are presented in Appendix 8 and these are for the final two periods of sampling only (November 2001 and February 2002). Results show that methane was detected only once (mean 2.63 mg $hr^{-1}m^{-2}$) during sampling and this was from the heated block (Block 5) in November 2001. The detection of methane coincided with a particularly heavy period of rain extending from August through to the end of October and it is possible that waterlogging of Block 5 took place leading to anaerobic conditions and the emission of methane. Heating of the bed may have made Block 5 more susceptible to creating the appropriate conditions for the growth of the methane forming bacteria to enable this to happen but understanding the mechanism behind this is beyond the scope of the project.

It would appear that the release of nitrous oxide from the surface of the beds, rather than methane, is much more problematic. For example, the range of nitrous oxide fluxes found during the project for Block 5 was 1.24 to 4.75 mg $hr^{-1}m^{-2}$ and this can be compared to other emission sources such as the range of fluxes reported for garden soil at 0.0031 to 0.031 mg $hr^{-1}m^{-2}$.

Clearly the issue of nitrous oxide emissions from vermicomposting is a potentially serious and, as yet, unrecognised problem. There is a pressing need to investigate the extent of the problem as soon as possible and to identify mitigation options, if appropriate. Research undertaken for this project, has identified vermicomposting as one of the most significant point sources of nitrous oxide emissions yet discovered. For example, riparian zones in the UK associated with intensive agriculture have been identified as the largest emitters of nitrous oxide to date, with levels of N_2O – N of around 38 kg $ha^{-1}yr^{-2}$. Recent emission figures for N_2O – N from vermicomposting have been found to many times greater than this at 275 kg $ha^{-1}yr^{-2}$. Although the total area of land devoted to vermicomposting operations would never be comparable to areas of riverbank in sensitive, agriculturally intensive locations, the first vermicomposting operation larger than 1 ha in area has already been established.

8. Summary and conclusions

8.1. The vermicomposting evaluation project described in this report had a number of aims:

- 8.1.1. The project sought to investigate the technical performance of outdoor vermicomposting, using a specifically designed bed system, which facilitated the research methods employed.
- 8.1.2. The project identified low processing temperature as a limiting factor and investigated bed heating as a method of enhancing performance.
- 8.1.3. The environmental impact of the outdoor vermicomposting system was evaluated in terms of leachate production and greenhouse gas emissions.
- 8.1.4. Ways of mechanising the process were explored with particular emphasis on waste application to the processing beds.
- 8.1.5. The cost-effectiveness and market potential of outdoor vermicomposting systems was assessed, with particular regard to basing the study on new technical knowledge gained during the course of the project and practical techniques developed.

8.2. An outdoor, experimental vermicomposting system was designed and installed comprising 400 m^2 of waste processing beds. Eight separate blocks of beds were constructed to enable comparisons between each block to be made. Blocks were sub-divided into 5 individual beds to allow for replication. Each block contained a leachate drainage and collection system. The environmental impact of leachate and greenhouse gas emissions was undertaken. Beds were unheated apart from one complete block, which was heated during the colder months only. Air and bed temperatures were continuously monitored. Beds were inoculated with known densities of earthworms and populations were rigorously determined every eight weeks.

8.3. Following construction of the vermicomposting beds, the monitoring and experimental phase of the project commenced on 1st January 2001. The experimental phase duration was 56 weeks.

8.4. Air and bed temperatures were monitored continuously throughout the year. For the unheated blocks the average temperature of the beds closely reflected prevailing air temperatures. For the first 20 weeks of the project (winter and spring) and the final 10 weeks of the year (winter) the average temperature of the unheated beds was 7.2 °C. This 30 week period represents around 60% of the year. The average temperature for the heated beds, during this same 30 week period, was controlled at 13.8 °C. For the hottest summer months, the average temperatures in the centre of the beds were around 20 to 25 °C, but the maximum temperature recorded in the core of the beds was 32 °C. The earthworm species used during the research was *Dendrobaena veneta.* Its optimum temperature for growth and reproduction is considered to be 20 to 25 °C while temperatures above 35 °C are thought to be lethal.

8.5. The performance of the unheated beds in terms of producing earthworms and off-spring was relatively poor. The majority of beds contained initial starter cultures of 1 kg or 2 kg earthworms per m^2 of bed. For these beds, the weight of earthworms after six months had declined to around half of the initial weight and this was maintained for the duration of the project. The first significant numbers of cocoons and hatchling earthworms were recorded after 16 weeks and 32 weeks respectively. The adult population of earthworms began to increase after week 32 due to the presence of the newly produced hatchlings but then declined rapidly by the end of the project. It is estimated that the sustainable population of earthworms that this unheated system would support would be around 2 kg earthworms per m^2 of bed. This is similar to other commercial systems that were investigated and this would be adequate for processing a limited amount of waste and could produce some earthworms for harvesting in the longer term. Migration of earthworms out of the beds was observed and this would appear to significantly reduce earthworm numbers.

8.6. Heating the beds greatly increased earthworm populations compared with not heating. For example, after the first 24 weeks in operation, the number of hatchling earthworms in the heated beds was approximately 40 times greater than in the unheated beds. The heated beds show the potential to support a working earthworm density of at least 4 kg per m^2 of bed and this could be achieved after one year. It has been estimated that a possible 3 kg of mature earthworms per m^2 of bed could be harvested per year from such a system. However, this will only be achieved if earthworms are contained within the beds and migration prevented. Periodic mass migration of earthworms out of the beds was observed on one occasion resulting in the loss of an estimated one third of the population of adult earthworms.

8.7. The waste applied to the processing beds was potato slurry. When the heated beds had become established the beds processed approximately 1.2 kg potato slurry per m^2 of bed per day. The waste applied to the processing beds was potato slurry. When the heated beds had become established the beds processed approximately 1.2 kg potato slurry per m^2 of bed per day. This is equivalent to 0.6 kg of waste being processed by 1 kg of earthworms per day. It is estimated that at least 0.8 kg of waste per kg of earthworms should be achievable. For a heated bed with a working population of around 4 kg earthworms per m^2 of bed, a processing rate of approximately 3.2 kg waste per m^2 of bed per day should be possible.

8.8. The waste potato slurry applied to the beds was processed by the earthworm populations in the bedding material. The resulting mix of earthworm casts and bedding is termed vermicompost. When compared with typical green waste compost the vermicompost was found to be richer in nitrogen and other valuable plant nutrients. If vermicomposts were eligible for the Composting Association *Compost Standards* scheme or BSI PAS 100, the vermicompost produced during the project would have met the requirements for the parameters tested.

8.9. The environmental impact of vermicomposting was investigated. The vermicomposting system produced a significant volume of leachate during the project and the amount would have been broadly related to rainfall. While the leachate appeared to have the potential to pollute, it was found to be less polluting compared with typical leachate from composting sites. Vermicomposting leachate was found have a consistently low BOD, although COD was moderately high. It contained useful concentrations of plant nutrients making it potentially useful as a liquid fertilising medium, if used with care.

8.10. Greenhouse gas emissions were monitored. Methane emissions were only detected during severe waterlogging of beds. However, research carried out during this project has identified vermicomposting as one of the most significant point sources of nitrous oxide emissions yet discovered. Nitrous oxide is a powerful greenhouse gas**.** There is a pressing need to investigate the extent of the problem as soon as possible and to identify mitigation options, if appropriate.

8.11. Research into mechanised methods of applying waste slurries to processing beds was undertaken and a successful system was developed.

9. Recommendations

9.1 It is recommended that vermicomposting systems should be operated as waste processing facilities that also have the potential to produce a limited amount of marketable earthworms. Maximising earthworm production is not compatible with maximising waste processing rates.

9.2 It is recommended that research is undertaken into devising effective methods of containing earthworms in the processing beds. Despite installing a typical containment device for this project, it was estimated that on one particular occasion, over one third of the adult earthworms migrated from an experimental block. Other separate mass migration events also occurred.

9.3 It is recommended that consideration is given to stabilising conditions in processing beds so that the earthworm populations are given every chance to develop. In particular, periodic waterlogging of processing beds regularly took place during the project and prevention of rainfall entering beds should be a priority. If conditions in the beds are hostile for earthworms, it is likely that more effective containment methods will only lead to increased mortality.

9.4 It is recommended that processing beds are heated to at least 15 °C during the coldest months of the year. Methods of heating will vary depending on local conditions but insulating beds as a minimum first step should be a priority.

9.5 It is recommended that research is continued into identifying better methods of preparing and applying waste to the processing beds.

9.6 It is recommended that the emission and mitigation of greenhouse gases (nitrous oxide) from vermicomposting is investigated as a matter of priority.

9.7 It is recommended that a significant programme of research into large-scale vermicomposting is undertaken and that the findings are made available to the rapidly developing vermicomposting sector.

Part 2

Financial Evaluation and Market Potential

Prepared by Urban Mines Ltd with contributions from Steve Ross Smith (WRC) and Jim Frederickson (OU)

1. Foreword

The scientific and technical research programme described in this report focused mainly on large-scale vermicomposting systems used for waste treatment, as compared with operations dedicated to the production of compost or worms. The research has also given the opportunity to undertake an assessment of the design, costs and hence commercial feasibility of a vermicomposting system, operating mainly as a waste treatment facility.

Research into large-scale vermicomposting systems is comparatively new in the UK and since the facilities at WRC have recently become established, only a preliminary evaluation of commercial feasibility was possible at this stage. In addition, the basis of the evaluation was the experimental system developed at WRC and clearly this does not represent the full spectrum of vermicomposting options which are available. Finally, it should be noted that there are many different ways of operating vermicomposting systems and operational criteria will depend heavily on the required outputs and the commercial aims and objectives underpinning the process. The system which was evaluated, placed most emphasis on waste management and maximising waste processing rates with less focus on maximising the production and harvesting of worms. Hence, the following preliminary evaluation should be viewed as an analysis of a very specific system of vermicomposting, operating in a particular way and subject to various research constraints.

Also contained in this section is a general market summary, which attempts to identify some of the potential customers for vermicomposting and related products and services. This summary is not comprehensive, but it attempts to evaluate which customers, products and services that could be targeted by the WRC and commercial operators of vermicomposting systems in the future.

2. Financial evaluation

The approach to the evaluation below is to estimate the gate fee (price per tonne of waste processed) that is required to enable the vermicomposting system to break-even after 12 months in operation. The vermicomposting system was set up to maximise waste processing rates rather than the production and harvesting of worms.

The financial details given below mainly include the direct costs of operating the vermicomposting system but other related overhead costs such as administration and management, marketing and office costs etc. are estimates only. However, while many of the direct costs have been derived directly from research and experience at WRC, such as processing rates and bed heating costs, direct income has been estimated and "best" and "worse" case scenarios have been used to estimate revenues.

Assumptions

It is assumed that the system is operated mainly as a waste processing facility, rather than for the production of compost or worms. However, as for similar commercial operations, limited harvesting of compost and worms is assumed. In this scenario, processing beds are stripped every 12 months to allow extraction of vermicompost and harvesting of mature earthworms, using similar equipment to Figure 3 (page 17). For the purposes of this evaluation, it is further assumed that a full-scale facility would comprise 100 blocks occupying a total area of 1 hectare (bed processing area = 0.5 ha). Most figures quoted are per block. Assumptions are as follows:

a) Processing temperature:	Average temperatures 15 °C (winter) 20 to 25 °C (summer).
b) Earthworm biomass:	4 kg/m^2 of processing bed (estimated carrying capacity).
c) Processing bed size:	As per WRC experimental system. One block comprising 5 individual beds (10 m^2). Total processing bed area = 50 m^2. Total working area required including paths = 100 m^2.
d) Waste processing rate	3.2kg of waste processed per m^2 of processing bed per day. Maximum 58 tonnes processed/block/year less 10% reduction due to harvesting worms = 52 t/yr processed.

e) Waste treated:	Assumed all suitable wastes are similar to potato sludge
f) Cost of processing beds:	Estimated £6,000 construction cost for 50 m^2 block of 5 worm beds (stocked with bedding, worms, heating cable and cover) plus infrastructure. Assumed annual depreciation cost of £600 per block.
g) Direct labour costs:	Bed operation and maintenance (1.5 hr per block per week: labour rate at £5.20 per hour), bagging/screening (approx. 7 days).
h) Bed heating:	Estimated electricity (winter heating) 7000 kWh (unit cost £0.07 per kWh). Annual electricity cost £490 per block.
i) Compost produced:	Vermicompost is mix of bedding material and worm casts. Assume each block produces 50 m^2 of vermicompost to a depth of 0.4 m giving a marketable total volume of 20 m^3. WRC could market vermicompost for £15 per m^3 in bulk as soil conditioner. Bagged, premium grade traditional compost retails for £40 to £120 per m^3 (Gardening Which, Jan/Feb 2003). Vermicompost is marketed commercially using the internet (10 litre bags) for equivalent of £180 to £560 per m^3. Assumed that minimum bulk price would be £15 per m^3 (worst case) while maximum bulk price would be £60 per m^3 (best case).
j) Earthworm production:	Assumed working density is 4 kg/m^2 and only mature worms are harvested (estimated to be 25%). Selling prices vary from approximately £5 per kg (worst case) to £10 per kg (best case).
k) Direct equipment costs:	Capacity of equipment is assumed to be 100 blocks. Estimated costs are given on basis of one block only.
l) Land rental price:	£222 rental per year per hectare for medium grade arable agricultural land in the East Riding of Yorkshire (Quote October 2002).
m) Overhead costs:	These are estimated costs only.

Table 1
Direct costs of operating the processing system

WRC expenses	Direct costs (per block) in £
Land Rental	2
Waste application and handling equipment	102
Screening/harvesting equipment	100
Electricity (bed heating)	490
Workshop rental	98
Labour (screening/bagging)	300
Labour (bed operation/ maintenance)	405
Depreciation of beds	600
TOTAL	£2,097

Table 2
Potential Income (per block)

WRC Income	Worst case	Best case
Compost sales (estimated 20 m^3/yr)	£300	£1,200
Earthworm sales (estimated 50 kg/yr)	£250	£500
TOTAL	£550	£1,700

Table 3
Gate fee required (per block - direct processing cost)

Details	Worst case	Best case
Direct processing costs	£2,097	£2,097
Total income	£550	£1,700
Net costs	£1,547	£397
Tonnes processed/yr	52	52
Gate fee per tonne required to break even	£30	£8

Table 4
Gate fee required (estimated overhead cost)

Details	100 block facility	1 block
Staff costs	£48,000	£480
Marketing/administration	£20,000	£150
Premises/facilities	£10,000	£150
Tonnes processed/yr	5,200	52
Gate fee per tonne required to break even	£15	£15

From the tables above it can be seen that the direct cost of operating the vermicomposting system, is estimated to be within the range £8 to £30 per tonne of waste processed. Hence, the overall net direct cost and final gate fee charged would be dependent on the revenues that can be obtained for the sales of worms and compost. At this time it is not possible to determine the overhead charges relating to the operation (business costs such as management, marketing and administration overheads) and figures quoted here are estimates only. The overhead charge is estimated to be £15 per tonne. Hence, waste providers would need to pay a gate fee of between £23 and £45 per tonne in order to process suitable waste using the technology and systems described in this report.

3. General Market Summary

This general market summary attempts to identify some of the potential customers for vermicomposting and related products and services. This summary is not comprehensive, but it attempts to evaluate which customers, products and services could be targeted by the WRC and commercial operators of vermicomposting systems in the future.

A general market analysis was carried out which explored the possible products that could be developed and markets that could be exploited by a commercial operator of large-scale vermicomposting systems. This analysis was split into 3 parts:

1. Marketing – who are the customers and what are the products and services that they will pay for?
2. Operations – How will the business work? What will be its management structure?
3. Financial – what will be the business costs, income, cash flow and funding requirements?

The key to this part of the plan is understanding customers. The tables in Appendix 9 address the key issues outlined below:

- Customer
- Assumed Need
    - Our current understanding
- Market size
    - Include source of information.
- Buying patterns
    - Where are the customers?
    - Who do they buy from now? Why? What do they pay?
    - When do they buy? Any seasonal elements?
- Product/Service
- Route to market
    - What are the preferred sales channels used by our customers?
    - Who are our potential partners?
- Gaps in WRC service
- Risk Analysis

4. Conclusions

The financial calculations in this chapter indicate that, based on the findings of the research alongside external market information and estimates of overhead costs, the cost of processing one tonne of waste at a dedicated vermicomposting facility could be in the range £23 to £45 per tonne. This means that a gate fee of £23 to £45 per tonne needs to be paid for the waste in order to process it using this vermicomposting technology.

There are a number of assumptions in these calculations that require further research before a more definitive evaluation can be made into the commercial viability of vermicomposting as a waste processing option.

Although financial calculations based on the cost per tonne of waste processed have been included in this chapter, they must be viewed in light of further research that needs to be undertaken in order for a true assessment of commercial viability to be made. Further research needs to focuses on a number of key aspects:

i) **Waste Types** – Do worms process all wastes at the same rate?

ii) **Bed Design** – How can insulation, drainage and covers be incorporated into the bed design to minimise heating requirements and dilution of leachate.

iii) **Feeding machinery** – How can preparation of food and feeding of worms be mechanised?

iv) **Vermicompost** – What is the true market value of vermicompost? Without inclusion in the Composting association or BSI PAS 100 standards, vermicompost will be unlikely to demand high market prices

v) **Migration** – How can migration of worms from beds be minimised?

vi) **Harvesting** – Although only a by-product, how can worms and compost be harvested more effectively and quickly without disruption to the processing of wastes?

vii) **Industry Wastes** – Where are they and in what quantities? Which wastes are a problem? What will industry pay for an environmentally friendly treatment of their wastes?

viii) **Legislation** – How will the price of landfill affect the commercial viability of vermicomposting as a waste processing option in the future? How will BSE regulations, post foot and mouth legislation and EU animal by-products legislation affect the processing of food wastes with a meat content in a non thermophylic environment.

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Appendix 1

Location of probes in Blocks 1, 3 & 5

Probes 1, 3 & 4 are all above bedding level in beds b, c & d
Probes 5, 7 & 8 are in the bedding in beds b, c & d

Probe 2 is above 3 in block c
Probe 6 is above 7 in block c

Bed b has probes 1 & 5
Bed c has 2, 3, 6 & 7
Bed d has 4 & 8

----- = upper bedding level

Bed a	b	c	d	e
		2		
	1	3	4	
		6		
	5	7	8	

Appendix 2

Comparison of WRC findings with other unheated systems

As part of the overall project, the old outdoor vermicomposting beds at WRC, which had been purchased as a commercial operation had been sampled at the start of the research project and their earthworm populations determined. In addition, another commercial vermicomposting operation was identified in the south of England and its operating characteristics monitored. Both systems had been inoculated with *Dendrobaena veneta* in the month of December with around 0.5 kg of earthworms per m^2 of bed and both had been in operation for approximately 27 months when sampled by the Open University. It is interesting to note that even after more than two years of undisturbed earthworm population development, neither operation had produced sufficient numbers of large, mature earthworms to allow commercial harvesting to commence. It is likely that all outdoor, uncovered vermicomposting systems would be subject to poor performance and periodic migration of mature and immature earthworms from beds.

Results from the sampling exercise showed that the old WRC beds had approximately 4,750 earthworms per m^2 of bed with an average individual weight of 0.4g. Total weight of earthworms was therefore 1.9 kg per m^2 of bed but only 3% of these were mature specimens, greater than 1g in weight. In the other example, the beds had approximately 4,300 earthworms per m^2 of bed with an average individual weight of 0.5g giving a total weight of earthworms of around 2.2 kg per m^2 of bed. This time 10% of these were estimated to be mature specimens, greater than 1g in weight. Cocoon numbers were also estimated to be 6,500 cocoons per m^2 of bed. Both of these results from existing operations, begun in the same month of the year, appear to be very similar to the predicted population profile for the unheated beds as discussed above. The main difference between the three operations is that the unheated experimental beds at WRC were initially inoculated with twice the weight of earthworms compared with the two commercial systems. However, as shown in Figure 11, the earthworm population in the experimental beds declined steadily over the first few months to under half of the original level. Hence, it is possible that the carrying capacity in terms of mature and larger immature earthworms in these types of unheated beds over winter is only around 0.5 kg per m^2 of bed.

The unheated experimental beds at WRC and the comparison operations were started during the winter months. With the WRC beds the initial low winter temperatures clearly reduced the system's performance. If the beds had been started in late spring when air temperatures were rising, the beds would probably have performed much better initially, in terms of producing high numbers of cocoons and hatchlings. However, with the onset of low air temperatures in autumn and winter it is highly likely that very little additional earthworm growth and reproduction would have taken place for the remaining six months of the year. Hence, it is likely that overall performance over the full year would not have been much different compared with the results presented in this report. However, the date on which outdoor, unheated systems are begun may have an effect on their short to medium term performance. Certainly with very low temperatures prevailing for most of the year in many areas, it might be sensible to start unheated vermicomposting operations at a time in the year when the starter culture of earthworms have the best possible conditions.

Appendix 3

Characteristics of Potato slurry

<u>Potato slurry was taken from the tank as delivered</u>

It was sampled from the storage tank on 3 occasions. One of these was a fresh delivery, still warm from the factory (sampled 9.1.01), others samples were taken from older waste. The slurry was mixed before sampling, but settles in the tank.

Samples	pH	Electrical conductivity (mS/cm)	Dry solids (% total weight)	Organic matter (% dry weight)	Total nitrogen (% dry weight)
Sample 1 (fresh)	4.0	5.21	13.2	90.8	2.28
Sample 2	3.5	11.45	9.6	86.8	N/A
Sample 3	3.7	8.00	10.1	85.9	2.76
Mean	3.7	8.22	10.9	87.9	2.52

Water Extractable Nutrients (% dry weight)										
Samples	**Na**	**NH_4**	**K**	**Mg**	**Ca**	**Fl**	**Cl**	**NO_3**	**PO_4**	**SO_4**
Sample 1 (fresh)	0.05	0.01	1.04	0.04	0.00	1.20	0.42	0.07	0.12	0.19
Sample 2	0.06	0.21	1.64	0.06	N/A	1.49	0.19	N/A	N/A	0.09
Sample 3	0.03	0.26	3.82	0.12	0.00	0.72	0.31	0.005	0.04	0.13
Mean	0.05	0.16	2.17	0.07	0.00	1.14	0.31	0.04	0.08	0.14

Appendix 3 (continued)

Potato slurry taken from the surface of beds in Block 5

Samples	pH	Electrical conductivity (mS/cm)	Dry solids (% total weight)	Organic matter (% dry weight)	Total nitrogen (% dry weight)
Bed 1	5.1	7.0	10.8	88.0	3.35
Bed 2	5.3	8.1	10.6	88.3	3.37
Bed 3	4.8	8.8	11.4	87.2	3.84
Bed 4	4.4	8.1	11.5	88.5	3.64
Bed 5	4.6	8.9	11.1	87.3	3.57
Mean	4.8	8.2	11.1	87.9	3.6

Water Extractable Nutrients (% dry weight)										
Samples	Na	NH_4	K	Mg	Ca	Fl	Cl	NO_3	PO_4	SO_4
Bed 1	0.10	0.10	1.75	0.07	0.07	0.30	0.24	0.03	0.11	0.03
Bed 2	0.04	0.52	1.57	0.02	0.02	0.32	0.17	0.00	0.25	0.05
Bed 3	0.25	0.29	2.60	0.22	0.00	0.50	0.36	0.00	0.24	0.06
Bed 4	0.26	0.24	1.95	0.04	0.00	0.65	0.27	0.00	0.18	0.03
Bed 5	0.05	0.06	2.56	0.05	0.26	0.49	0.31	0.00	0.13	0.06
Mean	0.14	0.24	2.09	0.08	0.07	0.45	0.27	0.01	0.18	0.05

Appendix 4

Chemical characteristics of vermicompost

<u>Changes in bedding over time</u>: various parameters

Samples (mean values)	**pH**	**Electrical conductivity (µS/cm)**	**Dry solids (% total weight)**	**Organic matter (% dry weight)**	**Total nitrogen (% dry weight)**	**Bulk density (kg/litre)**
Bedding only (start of project)	6.8	104	23	82	0.84	0.4
Bedding plus earthworm casts (August 2001)	7.8	404	21	83	1.57	0.5
Final vermicompost (February 2002)	7.3	462	17	80	1.78	0.6

<u>Changes in bedding over time</u> : Nutrient analysis

	Water Extractable Nutrients (% dry weight)				**Total Nutrients (% dry weight)**	
Samples (mean values)	**NH_4**	**K**	**NO_3**	**PO_4**	**P**	**K**
Bedding only	0.00	0.1	0.00	0.14	N/A	N/A
Bedding plus earthworm casts (August 2001)	0.04	0.24	0.04	0.09	N/A	N/A
Final vermicompost (February 2002)	0.00	0.68	0.62	0.24	1.66	0.86

Appendix 4 (continued)

Pytotoxicity test on vermicompost leachate: cress seed bioassay test
(Samples collected February 2002)

Block	Root elongation (% of control)	Germination (% of control)	Germination Index (%)
Block 1	74.3	91.7	68.2
Block 2	78.1	93.3	72.9
Block 3	58.0	83.3	48.3
Block 4	74.0	105.6	78.1
Block 5	47.2	86.1	40.7
Block 6	68.4	97.2	66.5

Appendix 5

Vermicomposting leachate characteristics

Leachate Characteristics (mean of samples collected every 8 weeks)

Block	pH	Electrical conductivity (µS/cm)	Suspended solids (mg/l)	5-day BOD (mg/l)	COD (mg/l)
Block 1	7.8	2400	175	25	2063
Block 2	7.7	2800	69	21	2099
Block 3	7.9	2500	93	23	2050
Block 4	7.4	2300	117	104	1955
Block 5	7.8	3000	89	22	2124
Block 6	7.5	2800	136	59	1793

Leachate characteristics (mean of samples collected every 8 weeks)

Block	Na (mg/l)	NH_4 (mg/l)	K (mg/l)	Mg (mg/l)	Ca (mg/l)	Cl (mg/l)	NO_3 (mg/l)	PO_4 (mg/l)	SO_4 (mg/l)
Block 1	65.4	0.0	768.6	48.9	69.2	129.3	199.6	160.6	35.2
Block 2	33.7	0.0	910.2	66.9	93.7	130.1	259.9	181.4	42.0
Block 3	38.8	0.0	823.2	60.2	88.2	141.3	283.3	163.7	60.4
Block 4	45.9	0.0	711.1	64.6	114.6	124.4	127.2	168.7	41.8
Block 5	44.1	0.0	1020	66.6	100.6	179.9	236.7	121.9	67.4
Block 6	53.3	0.0	932.3	70.9	101.7	194.5	211.1	167.9	46.2

Appendix 5 (continued)

Leachate collected per batch

Date	pH	Electrical conductivity (mS/cm)	Suspended solids (mg/l)	5-day BOD (mg/l)	COD (mg/l)
22.3.01	7.5	1.1		35	361
18.7.01	7.5	2.5		42	3304
14.8.01	7.7	3.1		21	2180
12.9.01	7.9	3.1	140	44	2203
15.11.01	8.2	3.6	107	46	1727
14.2.02	7.6	2.6	103	27	866

Leachate collected per batch

Date	Na (mg/l)	NH_4 (mg/l)	K (mg/l)	Mg (mg/l)	Ca (mg/l)	Cl (mg/l)	NO_3 (mg/l)	PO_4 (mg/l)	SO_4 (mg/l)
22.3.01	47	0	279	46	38	42	14	141	29
18.7.01	35	0	901	71	93	149	61	139	7
14.8.01	65	0	769	71	141	163	242	122	128
12.9.01	58	0	1191	73	131	202	157	134	51
15.11.01	36	0	1140	62	91	152	287	194	63
14.2.02	24	0	881	49	76	169	718	178	55

Appendix 6

Rainfall year 2001

(Source Environment Agency)

STATION NAME (HOOK)	Jan	Feb	Mar	April	May	June	July	Aug	Sept	Oct	Nov	Dec	Total
Total monthly rainfall (mm)	27.5	87.2	38.2	70.3	25.5	39.1	23.6	86.2	75.8	80.1	32.7	18.6	604.8
Mean daily rainfall each month (mm)	0.9	3.1	1.2	2.3	0.8	1.3	0.8	2.8	2.5	2.6	1.1	0.6	

Appendix 7

Characteristics of compost leachate taken from two phases of composting

(Source Frederickson, J. (1998) Compost Leachate: effect of composting duration on its composition and on its use as a fertilizer. pp 107-111. *Proceedings of the International Conference on Organic Recovery and Biological Treatment)*

Leachate	**pH**	**Electrical conductivity (mS/cm)**	**5-day BOD (mg/l)**	**COD (mg/l)**	**NO_3 (mg/l)**	**NH_4 (mg/l)**	**K (mg/l)**	**P (mg/l)**	**Ca (mg/l)**	**Mg (mg/l)**
Leachate (0-6 weeks of composting)	5.7	7130	4214	10839	8	147	1743	48	244	60
Leachate (0-6 weeks of composting)	6.8	5623	1068	5059	6	51	1639	14	131	25

Appendix 8

Mean fluxes of methane and nitrous oxide from surface measurements

Blocks	**Block 3** **mg $hr^{-1}m^{-2}$**	**Block 5** **mg $hr^{-1}m^{-2}$**	**Block 6** **mg $hr^{-1}m^{-2}$**	**Control** **mg $hr^{-1}m^{-2}$**
NITROUS OXIDE				
November 2001	2.78	3.38	2.13	0.40
February 2002	3.25	2.23	4.0	N/D
METHANE				
November 2001	N/D	2.63	N/D	N/D

N/D = Not detected

Appendix 9

Market Analysis

Worm Farmers

Assumed Need	Product / Service	Strengths	Route to Market	Gaps	Risks
An understanding of latest research and best practice	Training courses	• Latest research	• Direct selling • Via local college • Via Open University	• No curriculum • Not accredited • No seminar facilities • No teaching competencies • Only "our" latest research	• Technology needs to be constantly updated to make sure courses were giving unique offering
Technical advice (incl. Provision of beds etc.)	Consultancy Service	• Ability to conduct research • Little advice currently available • Ownership of ***shanks first*** Report	• Direct selling • Via Composting Association • Via NFU • Via community recycling network	• Credibility without OU? (depends on expectation & sophistication of customer)	• Demands lot of time up front • Technology needs to be constantly updated
Less labour-intensive	Development of technology	• No known alternatives to	• Direct selling • Joint marketing	• No working prototype yet	• Much work and funding required up front

Assumed Need	Product / Service	Strengths	Route to Market	Gaps	Risks
operations		hand picking available • Ability of SRS to develop machinery	with a farm machinery company	• No funding to develop one • Engineering expertise	• Work being done abroad is constantly improving
Someone to conduct research programmes	Contract Research	• WRC facilities • Collaboration with Open University	• Direct selling • Via Composting Association • Via NFU • Via community recycling network	• Need lab back-up	• Scheme may have little credibility without Open University
A Book of Best Practice in Vermiculture	A Book of Best Practice	• Involvement in latest research	• Publishers • Open University Press • Compost Association • Website	• Ability to write at appropriate level for publication	• Would need constant updating
Management Information System for bed operation	Management Information System based on research findings (Software)	• Detailed research data	• Direct selling • Via Composting Association • Via NFU • Via community recycling network	• No current product (but easy to develop)	• MIS would have to be sold with WRC developed system of beds • Easy to copy

Food Processors

Assumed Need	Product / Service	Strengths	Route to Market	Gaps	Risks
Their own waste treatment system (driver being changes to landfill legislation)	Provision of worm-beds and operational know-how	• Latest research • Experience of set up and running	• Direct selling	• System not optimised	• Strong competition from existing treatment routes • Customers won't commit to capital investment • Customers won't do their own waste treatment • Waste licensing issues
Treatment of food waste (driver being changes to landfill legislation)	Waste treatment toll service	• Experience and facilities	• Direct selling	• Bed capacity and willing at WRC	• Large operation • Capital cost • Would need waste management license

Academic Researchers

Assumed Need	Product / Service	Strengths	Route to Market	Gaps	Risks
Facilities where researchers could conduct their own research	WRC facilities and contract research	• Experience	• Direct selling	• Only know Open University	• Academic conflicts

Organisations that supply Home Composting Systems

Assumed Need	Product / Service	Strengths	Route to Market	Gaps	Risks
A Book of Best Practice in Vermiculture (to supply with their systems)	A Book of Best Practice	• Involvement in latest research	• Publishers • Open University Press • Compost Association • Website	• Ability to write at appropriate level	• Would need constant updating

Domestic Householders/Gardeners

Assumed Need	Product / Service	Strengths	Route to Market	Gaps	Risks
Treatment of household waste/production of own compost	New domestic vermicomposting system	• Latest research	• Garden Centres • Direct Selling • Through Local Authorities	• No design yet	• Complex products • Lots of competition from conventional composting systems • Liability for worms dying
A Book of Best Practice in Vermiculture	A Book of Best Practice	• Involvement in latest research	• Direct Selling • Garden Centres • Through Local Authorities	• Ability to write at appropriate level	• Would need constantly updating
Compost	Vermicompost	• Unique Green product • People moving away from Peat based products	• Via local garden centres ("pick your own compost") • Soil association. Links • Compost association links • B&G (PR value only)	• No standard approval for such compost	• Small market too small • Public liability from products made from waste • Animal by-products legislation
Fertiliser	"Worm Tea" (bed leachate)	• Excellent performance in simple trials	• Via garden centres	• No approval for such fertiliser • Consistency of product	• Public liability

Appendix 10

Domestic Worm Composting Bins

Individual householders can obtain home worm composters from a number of different sources. Many local Authorities supply wormeries to residents at subsidised prices, whilst there are many garden centres, mail order catalogues and web sites from which a home wormery can be purchased. The wormeries available vary greatly in function and success rates depend very much on the physical conditions in which the worms are kept and the kinds of waste they are fed.

Below is a list of places which sell home wormeries:

www.tallywackerfarm.co.uk – Sell different types of home wormery

www.wigglywigglers.co.uk – Sell large range of home wormeries and soil improving worms

www.worms.com – Sell the famous Can-O-Worms wormery

www.bullnet.co.uk – Sell home worm composters

www.greengardener.co.uk – Sell large range of wormeries. All come with bedding and instructions for use with worms separate. They sell normal box style as well as worm tower which allows easy access to worms and compost.

www.recycleworks.co.uk – Sell worms and worm bins for home use

www.ollierecycles.com – Give information on how to build you own home wormery. Mainly targeted at children

www.originalorganics.co.uk – Sell worm bins and soil improving worms

Centre for Alternative Technology – Wales. Sell worm bins in shop and via mail order catalogue

LOCAL AUTHORITIES

Local Authorities which promotes the use of Home Wormeries to residents:

Royal Borough of Kensington and Chelsea – provide subsidised home wormeries to residents

South Hams District Council – Sells subsidised worm bins to residents for £31.00

Leicester City Council – Promotes the use of home wormeries. They do not sell subsidised bins but do give info on where one can be obtained from.

Trafford City Council – Provides subsidised worm bins to residents

Stockport Council – Provides subsidised worm bins to residents

EastBorne Council – Promote the use of wormeries