VERMICOMPOSTING BIOSOLIDS AND ORGANIC WASTES

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Abstract

Most biosolids produced at wastewater treatment plants in New Zealand, are currently put into landfills, were they can generate methane and produce leachate. Recent Government policy means that this disposal method cannot continue to be used and biosolids must be used beneficially. However, biosolids need to be stabilised before beneficial use. Using earthworms to break down organic wastes has gained momentum in the past decade. Earthworms and micro-organisms can be used in the vermicomposting process to stabilise many organic materials including biosolids.

This dissertation summarises information on vermicomposting obtained from a literature review and from visiting two large-scale commercial vermicomposting operations in Australia. Investigations assessed the potential of vermicomposting biosolids in New Zealand. Initially, the physical, chemical, and microbiological properties of three biosolids and four sewage sludges were measured. Worm acceptance of these materials were then determined. The four most promising materials from North Shore, Hamilton, Te Awamutu and Taupo were vermicomposted for 30 days using *Eisenia fetida*. The vermicasts produced were then evaluated in a glasshouse pot trial using ryegrass.

The biosolids characterised had widely different properties compared to sewage sludges from waste stabilisation basins. Biosolids had more plant nutrients, greater pathogens numbers (as indicated by *E. coli*) and lower heavy metal concentrations than sewage sludges. Biosolids were initially toxic to worms due to ammonium concentrations and required stabilisation for 14 days before acceptance whereas sewage sludges were acceptable within two days if cellulose (as paper or cardboard) had been added. Vermicomposting these materials for 30 days produced vermicasts with lower volatile solids, higher C/N ratio, and significantly reduced indicator pathogen concentrations than the starting material. Ryegrass trials showed that mixing vermicasts with soil significantly increased plant growth, mostly because of the soluble N content.

Trial results have shown that vermicomposting is an acceptable method for stabilising biosolids and produces a quality end product highly beneficial for land use.

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   Wellington, 14-16 April, 2003.

2. **Agronomic performance of vermicomposted biosolids.**
   Presented at enviroNZ03 Conference,
   New Zealand Water and Wastes Association,
   Auckland, 17-19 September, 2003.

Chapter 1 Overview

1.1 Solid Wastes

Wastes, or the residues of society, continue to be a growing problem in developed countries. The problem has become significant because these wastes are accumulating faster than the environment can handle them. Such "bottlenecks" cause pollution. Wastes can be classified as solid, liquid, or gaseous, and excessive accumulation can lead to pollution of land, water, and air.

Solid wastes from agricultural, commercial, industrial and residential sources have an obvious effect on the environment and simply burying these wastes in landfills is no longer publicly acceptable.

1.2 Solid wastes produced in community

The way a community has confronted its solid wastes is outlined below using Hamilton as an example. During 1995/96, a Waste Analysis Protocol (WAP) characterised community wastes for the Ministry for the Environment (MfE). The WAP findings by the Hamilton City Council (HCC) estimated that the solid wastes disposed in the city (Horotiu) landfill was equivalent to 650 kg per person and that 72% of the waste stream had the potential to be used and recycled (HCC, 1999). The dominant waste components arriving at the landfill were 33% organic and 23% paper, while a further 16% were inorganic materials that could be recycled. The amount of organics that could be recycled each year equates to 364 kg per person.

Another source of solid organic wastes comes from treating community wastewater. This is called sewage sludge or, if destined for beneficial reuse, biosolids. Approximately 40,000 m^3 of wastewater is required to be treated each day in Hamilton (HCC, 2000). Although the wastewater stream is 99.9% water, after primary and secondary sedimentation there still remains 40 m^3 of slurry (3-4% solids) that requires further processing. This slurry is dewatered reducing the volume to 12 m^3 of biosolids daily. Thus, the annual volume of dewatered biosolids equates to 36 kg per person per year.

1.3 Community response to handling solid wastes

In New Zealand, communities are making efforts to reduce the degrading impact of these solid wastes and local authorities have implemented waste management plans. For example, the HCC Task Group investigating the city's waste issues listed the 5Rs of waste management in order of importance as: (1) reduction, (2) reuse, (3) recycling, (4) recovery, and (5) residuals disposal (Environment Waikato, 1999).

The HCC has four methods of minimizing waste and coping with the increasing amount of solid wastes being generated by the city:

1. Hamilton Organic Recycling Centre (HORC):

Green wastes (grass clippings, garden prunings, etc) are delivered to the site and composted into a high quality soil conditioner. In 1998, approximately 12,000 tonnes of green wastes were processed on site (HCC, 2000). These green wastes would normally have gone to landfill and contributed to gaseous emissions (mainly methane).

2. Hamilton Refuse Transfer Station and Recycling Centre:

This is where inorganic materials (glass, plastics, and metals) are recycled.

3. Horotiu Landfill:

Refuse is trucked to the landfill from the transfer station and placed in lined cells, capped with soil and eventually sown back into pasture.

4. Biosolids:

Dewatered biosolids are currently stored on an impervious surface for one year before being used. Maize and lily growers have readily accepted the material as a soil conditioner. Old stockpiles of sewage sludge have been used as capping material for daily cover at the Horotiu landfill (Marcus Shipton, HCC Wastewater Treatment Plant, pers. comm.).

1.4 Waste volumes

The total organic waste stream from Hamilton citizens is estimated to be 500 kg per year, and comprises:

Landfill organics	364
Green/garden wastes	100
Sewage sludge	36

Only 20% of the total organic waste stream (i.e. the green/garden wastes currently recycled by the HORC) is being beneficially used. Reuse of organic wastes, such as biosolids, has recently gained momentum because of the New Zealand Waste Strategy announced by MfE (Wigley, 2002) requiring that by December 2007, 95% of the sewage sludge/biosolids currently going to landfill be composted, beneficially used or appropriately treated to minimise the production of methane and leachate.

1.5 Scope of Dissertation

This dissertation focuses on the part of the organic waste stream that is not being beneficially, used namely sewage sludge and landfill organics. A biological process for stabilising organic materials called vermicomposting is explored by reviewing scientific research plus findings reported from commercial experience. The vermicomposting process, systems and operational factors are explored. This is followed by preliminary studies conducted at AgResearch, Ruakura Research Centre, Hamilton, on worm acceptance of sewage sludges and biosolids from local communities; characterisation of these sludges for their physical, chemical and microbiological properties with measurements before and after vermicomposting. The vermicasts produced from the sludges were then used in a glasshouse experiment to evaluate the agronomic effectiveness of vermicasts on plant growth, pathogen survival and heavy metal fate when added to a cropping soil.

Knowledge gained from visiting two large-scale vermicomposting operations in Australia during 2002 has been incorporated as well as personnel correspondence with several researchers, engineers and consultants from around the world.

Chapter 2 Vermicomposting

2.1 History of Vermicomposting

For thousands of years, farmers, gardeners, and plant enthusiasts have used earthworm castings to improve soil fertility and enhance plant growth and health (Herlihy, 2001). Using earthworms to accelerate decomposition of biodegradable materials is known as vermicomposting (Neuhauser *et al.*, 1979) or vermistabilisation (Loehr *et al.*, 1979). The Latin word for worms is *vermes* from which "vermi" is derived.

Vermicomposting stabilises biodegradable organic matter under controlled mesophyllic conditions (5-35°C) using the symbiotic action of specific worm species and micro-organisms. The worms maintain aerobic conditions in the mix, ingest solids, convert a portion of the organics into worm biomass and respiration products, and expel the remaining partially-stabilised soil-like products as castings (Loehr *et al.*, 1988). Vermicomposting is a sustainable technology that optimises the natural soil building biology and properties of earthworms to convert raw wastes into stable plant enriching vermicasts. Traditionally, only small amounts of vermicompost have been produced but with mechanisation specialist large scale operations are now economically possible. If the end product is producing worms for sale, the operation is called vermiculture.

In composting, aeration and turning operations are achieved mechanically whereas the principle difference in vermicomposting is that earthworms turn and keep the decomposing material aerobic (D'Alton, 2002). Many of the constraints of composting are overcome by replacing engineers and/or mechanical devices with earthworms, which is the basis of the success and reliability of vermicomposting.

Using worms to degrade organic wastes first gathered momentum in the early 1980s when an extensive research programme was undertaken by Dr Clive Edwards at Rothamsted in the United Kingdom. Dr Edwards later moved to Ohio State University and brought the basic vermicomposting concepts to the United States. Investigations into the capabilities of earthworms to process wastes and produce plant-growth enhancing media followed. Large-scale continuous flow

vermicomposting systems were designed to meet the criteria of ease of access, aerobicity, temperature control, and moisture control (Appelhof, 2003).

2.2 Earthworms

2.2.1 Worm species and characteristics

Earthworms are classified within the animal kingdom as a terrestrial phylum Annelid of the class Oligochaeta, which consists of over 7,000 species. Earthworms can best be classified by their behaviour and habitat. An Australian classification (Buckerfield, 1994) describes worm species occupying varying levels in soil and indicates their feeding behaviour as follows:

- Epigepic (surface dwelling) types that live at the surface in freshly decaying plant or animal residues.
- Endogenic (topsoil dwelling) types that live within the soil and injest soil to extract nutrition from degraded organic matter.
- Anecic (subsoil dwelling) types that burrow deep in the soil but come to the surface at night to forage for freshly decaying residues.

Compost worms differ from earthworms also by habitat by feeding close to the surface on organic matter rather than living in soil (Figure 1).

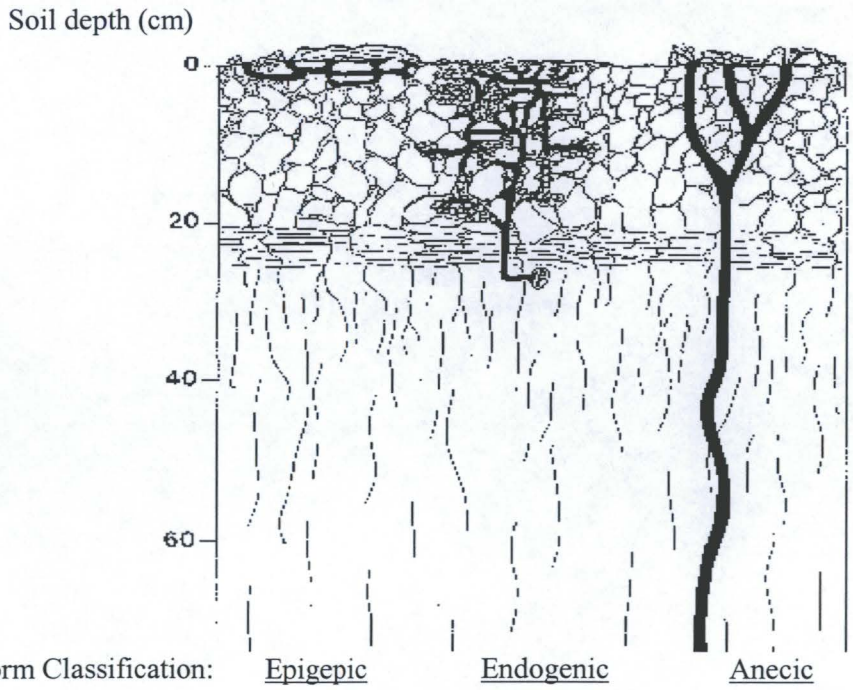

Figure 1: Classification of worms by habitat (from Trish Fraser, Crop and Food)

Eisenia fetida

Eisenia fetida, also known as the tiger or compost worm, are the most common species used in vermicomposting. It is a very prolific breeder, sexually maturing between 40 to 60 days, and laying a capsule with two to four eggs every 7 to 10 days. The eggs mature after 14 to 21 days, becoming fully able worms that can move and feed themselves immediately (Venter and Reinecke, 1988). The life cycle of *E. fetida* is shown in Figure 2 (Wilson, 1999).

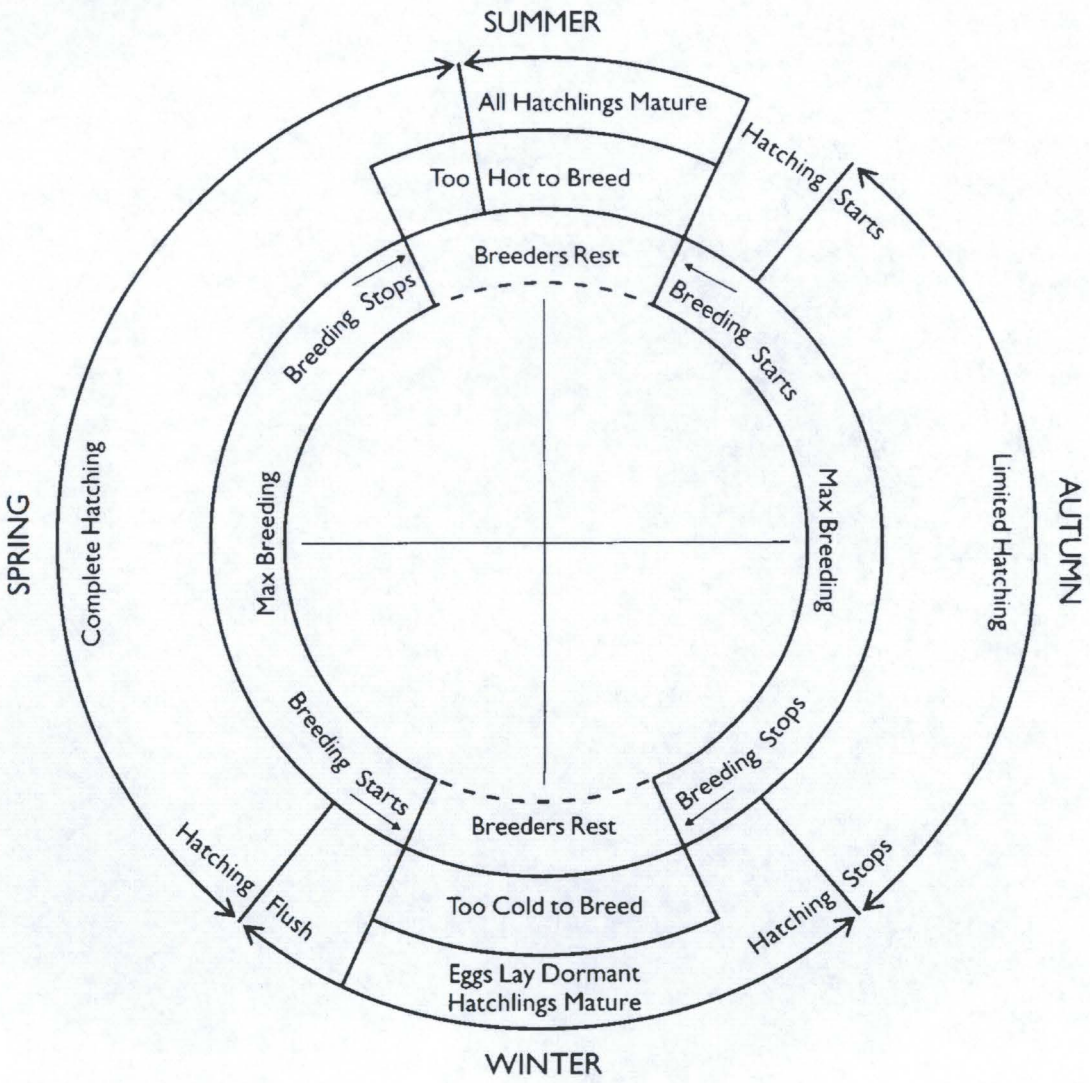

Figure 2: Life cycle of the Worm under Natural Conditions (from Wilson, 1999).

The reported dry weight of *E. fetida* ranges from 18% of live weight (Hartenstein *et al.*, 1980) to 20-25% (Sabine, 1983). The solids comprises 97% protein (or about 10% nitrogen), 2.1% lipid and 1.1% ash (Hatanaka *et al.*, 1983). Edwards *et al.,* (1985) reported a different composition of 60-70% protein, 7-10% fat, 8-20% carbohydrate and 2-3% minerals.

Neuhauser *et al.,* (1980a) describes the growth pattern of *E. fetida* as hatching from its cocoon about three weeks after fertilisation and following a logarithmic growth pattern. It grows slowly for about three weeks and then enters a rapid growth phase. The growth rate (or slope of the curve) is a useful index of the nutritional quality of its food. The rapid phase is then followed by a steady state maintenance phase or a phase of weight decline. The slope of the latter period can be used as an index to a property of the food related to starvation latency.

The average weight at hatching is 3 mg whilst an adult *E. fetida* can weigh 1330 mg when cultivated on dairy waste sludge cake (Hatanaka, *et al.*, 1983). As a general rule of thumb, 4,000 $\pm$ 2,000 worms weigh 1 kg, with the large variation in numbers depending on worm size. However, 1 kg of little worms eat about the same amount as 1 kg of larger worms. Further studies by Hartenstein *et al.,* (1981a) found that *E. fetida* grew on activated sludge from 3 to 10 mg liveweight at hatching to 792 mg ($\pm$ 142) after 8 weeks.

Eisenia andrei.

This species is very similar to *E. fetida* and is commonly used in vermicomposting. Growth and reproduction studies under identical conditions by Haimi (1990) found that both *E. andrei* and *E. fetida* were suitable for vermicomposting.

Lumbricus rubellus

This species is commonly found in NZ pastures under dung pats. However, attempts to use this species in vermicomposting have not always been successful for two reasons: a) they like to be in contact with soil and b) although active during autumn and winter, they disappear at the onset of hotter weather (Julie Dennis 'Worm Lady', Hamilton, pers. comm.).

Dendrobaena venata

These are large worms but are not very prolific and do not grow fast enough. They probably are the least suitable for breaking down organic matter (Edwards, 1988).

Other species

Several other worm species have been successfully used in vermicomposting under tropical conditions including *Eudrilus eugeniae* (African night crawler), *Perionyx excavatus*, and *Perionyx hawayana*. However, these species are not applicable to New Zealand conditions and are not discussed further.

2.2.2 Worm Growth

Edwards (1988) carried out laboratory trials on survival, growth and reproduction of worm species on animal, vegetable, brewery, paper wastes, and activated sewage sludge. Productivity of *E. fetida* was greater than *D. veneta* as cocoons required less time to hatch and reach sexual maturity (Table 1). Although *D. veneta* had heavier mature weights, *E. fetida* with a higher number of hatchlings and greater net reproductive rate, produced four times greater biomass than *D. veneta*.

Haimi (1990) reported that *E. andrei* grew faster than *E. fetida* under identical conditions. Although *E. andrei* produced more cocoons of higher viability, *E. fetida* produced more progeny per cocoon with the net result that mature *E. andrei* produced 5.7 hatchlings per week while *E. fetida* produced 4.0. Hatanaka *et al.*, (1983) had earlier studied *E. fetida* growth and found that increased biomass was associated with increased number of worms although average worm weight tended to decrease (Table 2).

Table 1: Growth characteristics of *E. fetida* and *D. venata* (from Edwards, 1988).

Measurements	*E. fetida*	*D. venata*
Reproduction		
Cocoons, number worms per day	3.8	1.6
% hatched	83	81
hatchlings, number	3.3	1.1
Net reproductive rate, worms per week	10.4	1.4
Life cycle		
Time for cocoons to hatch, days	32-73	40-126
Time to sexual maturity, days	53-76	57-86
Time egg to maturity, days	85-149	97-214
Biomass production		
Mean mature weight, mg	550	920
Minimum time to maturity, weeks	8.4	8.1
Biomass production, mg worms/week	680	160

Table 2: Growth of *Eisenia fetida* (from Hatanaka *et al.*, 1983).

Days	Number of worms	Increase in number	Average weight (g)	Total biomass (g)	Increase in biomass
0	5	1	1.33	6.7	1
30	5	1	1.33	6.7	1
70	165	33	0.18	35.5	5
90	240	49	0.35	90.7	14
120	365	73	0.60	222.7	33

2.3 Decomposing Organic Matter

2.3.1 Rate of decomposition

The rate that organic matter decomposes in vermicomposting is significantly faster than that in conventional composting. Worms appear to have a limited capacity to digest organic residues and it is believed that they get most of their nutritional needs by digesting microorganisms. Fungi, protozoa and algae appear to be the major sources of earthworm nutrition with bacteria playing a more limited role (Doube and Brown, 1998). Even though microorganisms are a major food source for worms, microorganisms and worms work together symbiotically to accelerate the vermicomposting process (Loehr, 1988). Worms play a vital role in creating optimum conditions for micro-organisms to establish and reproduce competitively (D'Alton, 2002).

Once ingested material enters the intestinal tract, it is subjected to various enzymes, intestinal mucuses, antibiotics and other microbiocidal substances. Different microorganisms are affected in different ways when exposed to these substances. Some substances are totally digested while others pass through the intestinal tract unharmed (Doube and Brown, 1998).

The size of organic matter particles are reduced by the various tumbling and grinding actions within the worm's digestion processes, converting a material with a relatively small surface/volume ratio into numerous particles with a larger surface/volume ratio (Lotzof, 2000). The consumed particles are fragmented which accelerates decomposition and mineralization with the vermicasts emerging as aerobic aggregates aiding drying and preventing malodour development (Hartenstein and Hartenstein, 1981; Kale, 1998).

The vermicast and burrows are lined with carbon and protein rich mucus, which increases the nitrogen content of the surrounding material and provides nourishment for microbes (Scarborough, 2000). These conditions, combined with an aerobic environment, form a very favourable growth medium for microorganisms (Doube and Brown, 1998; Kale, 1998). This appears to be a vitally important aspect of a successful vermicomposting system processing

activated sludges alone or mixed with other materials, especially when considering reduction/elimination of pathogens (Scarborough, 2000).

Gut load in *E. fetida* was reported as 3-5% (gut load to live worm weight) for sludges and manures, between 30-70% for soil, and independent of worm size (Hartenstein, 1981). Transit time (defined as the time for ingesta to pass from mouth to anus) also appeared to be independent of earthworm size and was 2.5 hours irrespective of whether the food source was soil or cellulose.

2.4 Environmental factors

2.4.1 Carbon/nitrogen ratio

Carbon/nitrogen ratios are not as critical for vermicomposting as for composting. Lignin breakdown is accelerated so excess nitrogen is rarely an issue in vermicomposting. For example, a high paper/low sludge mix that would normally be unacceptable for conventional composting can be used in vermicomposting because a ready supply of nitrogen is available to microorganisms whilst they maintain a high rate of carbon degradation (D'Alton, 2002).

Sewage sludge has a C/N ratio at the low end of acceptable - 6 for activated sludge and 16 for digested sludge. Therefore, it needs to be conditioned by mixing in wood chips, sawdust, bark or dry compost (Wilson, 1989). Sometimes these sludges have been mixed with municipal solid wastes (MSW), which have lower C/N ratios (40-80) and moisture contents (Wilson, 1989).

Investigations by Neuhauser *et al.*, (1980) found that *E. fetida* gained maximum weight in mixed cellulose and activated sludge systems when C/N ratios were 15-35. *Eisenia fetida* biomass was similar when cellulose was added to reduce the N content of sewage sludge (to 1.2%) to those fed sludge alone (4.8% N). Hartenstein (1980) concluded that *E. fetida* derived considerable amounts of energy from cellulose and that it may selectively remove larger proportions of microbes from the ambient cellulose matrix.

High levels of nutrients in the feed material, e.g. C/N ratio <15, can rapidly deplete oxygen and produce the anaerobic conditions that inhibit worm

activity and generate odours (Edwards, 1988). Excess nitrogen is volatilised as ammonia. Therefore, organic materials with available energy (i.e. low C/N ratios such as green wastes) should be uniformly mixed with carbonaceous materials low in available energy (i.e. high C/N ratios such as cardboard) to give the desired C/N ratio of about 20-25:1. The C/N ratios of some high nitrogen and high carbon feeds that could be used for vermicomposting are given in Table 3.

Table 3: Approximate carbon/nitrogen ratios of some organic wastes suitable for vermicomposting (from Rynk, 1992).

	C/N ratio		C/N ratio
High Nitrogen materials			
Horse manure	30	Sewage sludge	6-16
Pig manure	30	Food scraps	15
Cow manure	19	Broiler litter	14
Grass clippings	19	Vegetable wastes	12
High Carbon materials			
Newsprint	400-800	Paper pulp	90
Corrugated cardboard	560	Leaves	40-80
Sawdust, wood chips	440	Fruit wastes	35

2.4.2 Temperature, aeration and moisture

The optimum growth temperature for *E. fetida* was 25°C (Edwards and Lofty, 1972) whilst Kaplan *et al.,* (1980) reported maximum weight gains were achieved between 20 and 29°C. Some worm growers reported to Mitchell (1983) that optimum hatching occurred at 18°C and optimum growth at 25°C. Temperature has a marked effect on *E. fetida* cocoon production and hatching (Table 4). The maximum net productive rate of 8.4 worms per week occurred at 20°C and Edwards and Bater (1992) considered this an optimum temperature for using *E. fetida* to process organic wastes.

Table 4: Effect of temperature on reproduction rates of *Eisenia fetida* (from Edwards and Bater, 1992).

Temperature (°C)	Cocoons (number/ per worm/ per week)	Hatched (%)	Hatchlings per cocoon (number)	Incubation time (days)	Net reproductive rate per worm per week
10	Negligible	94	3.8	73	Negligible
15	1.8	91	3.8	50	6.2
20	**3.4**	**75**	**3.3**	**36**	**8.4**
25	3.8	55	2.6	32	5.4

Paley (2000) found that any changes in temperature of worm beds should be introduced gradually to maintain production. Commercial experience by Dr Scott Subler of Ohio State University, USA, identified that the heat capacity of worm beds is the limiting factor of how much to feed worms. The upper limits of heating are reached simply by feeding the worms at the rate at which they consume the material. Because castings are not totally stabilised they will still generate heat (Sherman, 2002a). As well as feeding based on the worms' consumption rate factoring in the bed temperatures is also required. Further research is continuing on balancing environmental controls of temperature and moisture for optimum worm activity. For example, using blower fans under the raised bed system means that heat can be drawn out of the worm bed through evaporative cooling, plus the castings are kept drier at the bottom (Sherman, 2002a). Bed temperatures above 35°C may result in worm migration out of the feedstock layer, leading to cessation in processing and possible system failure (Daniels, 2000). Some worm bedding designs are more effective in controlling bed temperatures than others because gas and heat exchange can occur on two surfaces. Worm bedding designs are discussed in Chapter 4.

Worms require an aerobic environment of not less than 10% free oxygen in the active layer of the system (Daniels, 2000). The continuous burrowing activity by worms provides an underground pipe network for constant aeration and also allows higher moisture levels than can be accommodated in normal composting, plus the production of ammoniacal and volatile sulphurous compounds is minimised (D'Alton, 2002). A light stirring of the top 50 cm of bedding every 2-3 weeks was recommended by Paley (2000) to allow any built-up gases to escape.

Edwards and Bater (1992) study showed that optimum growth of *E. fetida* occurred between 25-30°C and at moisture contents of 80-85% (Table 5) while Kaplan *et al.,* (1980) found maximum weight gains occurred over a wider moisture range of 70-85%. Further investigations (Venter and Reinecke, 1988; Dominguez and Edwards, 1997) found that optimum moisture levels varied between 80-90% in the active layer of the bed (where the feedstock is supplied) and between 30-70% in the bed material. Too low a moisture content can inhibit the worms' ability to process organic material while too high a moisture content can result in oxygen deficiency (Daniels, 2000).

Table 5: Effect of moisture and temperature on mean worm weights (mg) of *Eisenia fetida* (from Edwards and Bater, 1992).

Temperature	Moisture content of worm bed				
	70%	75%	80%	85%	90%
15 °C	230	420	580	610	340
20 °C	260	450	620	740	360
25 °C	280	480	640	**780**	490
30 °C	320	570	**760**	**820**	530

Commercial experience in California found large increases in worm numbers if an automatic drip irrigation system for moisture control was installed. Two lines of drip emitter hoses placed 30 cm above the 1 m wide worm beds were used to deliver water at a rate of 3 L/hour (Riggle, 1996). The optimum conditions for *E. fetida* from research findings (Edwards, 1988) and commercial experience (Lotzof, 2000) are summarised in Table 6.

Table 6: Optimum growing conditions for *Eisenia fetida*.

Condition	Requirement
Temperature	15-20°C (Limits 4-30°C)
Moisture content	80-85% (Limits 60-90%)
Oxygen requirement	Aerobic
Ammonia content of waste	Low: < 0.5 mg/g
Salt content of waste	Low: < 0.5%
pH	7-8 (tolerates range 5-9)

2.5 Feed sources

2.5.1 Organic wastes

Earthworms can break down most organic wastes although some wastes may need pre-treating (such as blending with biosolids) before vermicomposting (Edwards, 1995). Not all wastes support earthworm biomass equally. Neuhauser et al., (1980b) investigated the suitability of simple nutrients (oils, proteins, and carbohydrates), microorganisms, and organic wastes (food residues, manures, sludges, paper) as feedstocks for *E. fetida.* Simple nutrients were found to be unsuitable food sources and nutritional benefits were only derived from materials with high cellulose contents.

Organic wastes can be divided into the following six categories:

1 Animal manures

Cattle manure is an ideal worm feed once the solids are separated from slurries. High growth and reproduction rates can be achieved on fresh, urine-free, cattle manure provided anaerobic conditions are not created (Reinecke and Viljoen, 1990). Horse manure is an excellent medium for growing earthworms and needs very little modification. Piggery solids are the most productive waste for growing worms. These solids must be separated out and may need to be composted for two weeks if they contain high ammonia levels and/or inorganic salts. Likewise, poultry wastes can contain significant amounts of inorganic salts and ammonia. However, worms grow well provided poultry wastes are pre-treated (by composting or aging) and produce nutrient rich vermicasts.

2 Food processing and distribution wastes

Potato wastes, in the form of peel from the processed potato industry are an ideal growth medium without any further modification (Edwards, 1995). Spent mushroom compost is also a good medium. The worms can break down any straw and produce a finely structured material. Vegetable and fruit wastes from markets, restaurants, schools, etc, are ideal worm feed but require bulking agents such as cardboard to absorb excess moisture. Worms are especially fond of foods such as melons and pumpkins (Rhonda Sherman, North Carolina State University (NCSU), pers. comm.).

3 Paper and cardboard wastes

Paper and cardboard waste are good growth media, especially if they have been shredded. Cardboard is a source of cellulose, a polysaccharide derived from plant fibres (Paley, 2000). The glue used in cardboard boxes is often animal derived and sought after by worms (Riggle and Holmes, 1994). The Recycled Organics Unit, NSW, always shredded dry cardboard using a rotary shear shredder before mixing with food wastes to absorb excess moisture. The cardboard rapidly moistens and softens, making it amendable to vermicomposting (Mark Jackson, ROU, pers. comm.). Charred paper and the fluffy, wet by-product from cardboard recycling have also been successfully used as worm feedstock (Biocycle, 2002a). However, wood (also a cellulose source) is not suitable for *E. fetida,* which indicates that the ligneous components must be microbially or enzymically degraded to allow the cellulose to support earthworm growth (Hartenstein, 1980).

4 Industrial organic wastes

Pulp and paper solids have sufficient moisture to grow worms. It is processed quickly and allows rapid worm growth and multiplication. Worms can also quickly grow and multiply on brewery wastes (Edwards, 1995).

5 Urban wet wastes

Urban wet wastes such as grass clippings and leaves from residences or municipal sources (parks and reserves) are good growth media for worms, particularly if they are first macerated and thoroughly mixed.

6 Biosolids

These materials have high organic matter contents (~70%). Activated sludges are particularly popular and may need little modification. Biosolids and sewage sludges are discussed in greater detail in Chapter 3.

Whatever the food source however, it is important to remember the words of Dr Clive Edwards "worms derive their nutrients from the microbes and fungi that grow on the organic matter, not from the organic matter itself " (Riggle and Holmes, 1994).

2.5.2 Unsuitable food media

Animal manure and activated sludge castings cannot be re-ingested as a food source (Neuhauser *et al.*, 1980b). If worms are forced to ingest their own castings, mortality rises rapidly. Other unacceptable feed stocks include mixed food organics such as meat/poultry and dairy products. Raw seafood is also unsuitable because of odours (ROU, 2002). Meat scraps or bones, fish, greasy or oily foods, fat, tobacco, or pet manure should not be used and the amount of citrus fruit in vegetable scraps should be limited as they can cause the media to become too acidic (Rhonda Sherman, NCSU, pers. comm.).

Chapter 3 Biosolids and sewage sludges

3.1 Criteria for stabilisation

The three fundamental objectives for stabilising biosolids are to reduce pathogens, eliminate offensive odours, and eliminate the potential for putrefaction (Vesilind, 1979; Switzenbaum *et al.*, 1997). There must be an increase in the stabilisation rate for earthworms to be successfully used in stabilising biosolids. This is best demonstrated by increasing the rate that volatile solids are reduced. The goal of any biosolids stabilising system is to maximise this rate (Edwards, 1995). Another indicator is the increasing ash content in the sludge with time. Wilson (1989) reported that the C/N ratio can indicate product stability provided the initial C/N ratio was high.

Sludge decomposition can be increased two to five times (Dindal, 1978) because of the following physical, chemical and biological feeding interactions with *E. fetida*:

- earthworm feeding stimulates sludge breakdown
- earthworm feeding removes senescent bacterial colonies, which stimulates new bacterial growth
- the sludge is enriched by nitrogenous excretions
- microbial growth increases because bacteriostasis and mycostasis are eliminated
- oxygen penetration is enhanced
- mineral nutrients are added
- earthworm feeding influences interactions between the microflora, protozoa, and nematodes, thus increasing carbon and nutrient flux.

3.2 Contaminants

3.2.1 Pathogens

Sewage sludge can be a health risk because it may contain human pathogens such as *Salmonella, Escherichia coli*, and Helminth ova that survive the wastewater treatment process. Viable organisms can persist in soils. If

environmental conditions are idea for both harmful and beneficial microorganisms, pathogen populations such as *Salmonella enteriditis, E. coli,* and other *Enterobacteracae* are reduced with earthworm activity (Edwards, 1998; Lotzof, 2000).

Portuguese researchers (Ressetti *et al.*, 1999) found that when raw aerobic sludge mixed with sawdust underwent thermophilic composting the viability of helminth eggs was reduced by 93-100%, but after vermicomposting with *Eudrilus eugeniae* at 1 kg/m^2 density there was total reduction. When Scarborough (2000) mixed biosolids with green wastes it was found that vermicomposting reduced pathogens, enteric viruses and helminth ova populations by a far greater rate than when natural attrition occurred. Eastman et al., (2001) observed that pathogens in a 1:1.5 part biomass: biosolids wet weight mix were reduced by *E. fetida* to USEPA Class A biosolids stabilisation standards (Table 7).

Table 7: Pathogen reduction achieved after vermicomposting biosolids for six days (from Eastman et al., 2001).

	Pathogen reduction (log scale)	
Pathogens	Control	Vermicomposted
Faecal coliforms	1.6	6.4
Salmonella	4.9	8.6
Enteric viruses	1.8	4.6
Helminth ova	0.6	1.9

Dan Holcomb of Oregon Soil Corporation and Dr Clive Edwards investigated pathogen survival (*Salmonella, E. coli*, and faecal coliforms) by vermicomposting biosolids and found that these pathogens were reduced to non-detectable levels. Another finding was that the vermicasts produced could not be effectively reinnoculated with pathogens, unlike aerobic compost (Tom Herlihy, Joyce Engineering, USA, pers. comm.).

3.2.2 Heavy metals

Biosolids contain heavy metals with their concentrations being dependent on activities within the wastewater catchment. Copper (Cu) and zinc (Zn) are the

most common metals because they are used extensively in plumbing systems and therefore end up in the wastewater. Hartenstein (1980) found that cadmium (Cd), nickel (Ni), lead (Pb), Zn and Cu can accumulate in *E. fetida* tissues so care must to be taken when using worms in sludge management. A later study (Malecki et al., 1982) supported the earlier findings that Cd had the most deleterious effect on *E. fetida* in the short-term (8 weeks), followed in decreasing order, by Ni, Cu, Zn, and Pb. These adverse effects were thought to be partially related to solubility. Deleterious effects on reproduction were also found with metals in the same order over longer term studies (20 weeks) (Malecki et al., 1982). However, adding high levels of chromium (Cr) and Pb to activated sludge did not seem to affect *E. fetida* (Hartenstein et al., 1981).

Accumulation is considered to occur when the ratio of metal content in tissues to that in the environment exceeds 1.0 (Ireland, 1983). When Hartenstein (1980) evaluated seven metals only Cd accumulated in *E. fetida*. Heavy metal concentrations in *E. fetida* removed from sludges over 2-28 weeks (Table 8) reflected the heterogeneity of materials and the highly dynamic interchange of metals between the abiotic and biotic components of the sludge and the earthworms (Hartenstein, 1980).

Table 8: Heavy metal concentrations (mg/kg) in waste activated sludge and in *Eisenia fetida* removed from sludge over 2-28 week period.

Heavy metal	Sewage sludge	Earthworm
Cadmium	12-27	8-46
Chromium	200-650	1-13
Copper	380-610	20-150
Lead	160-900	1-53
Nickel	72-147	2-46
Silver	7-16	1-4
Zinc	875-2,100	68-210

A study on the effect of sub-lethal concentrations of Cd, Cu, Pb, Ni, and Zn on *E. fetida* growth and reproduction during and after exposure found that the worms had compensatory growth once the metals were removed. However,

reproduction rate did not recover fully. This compensatory growth is important in commercial vermicomposting as it shows that the worms can recover from accidental contamination of heavy metals (Neuhauser *et al.*, 1984).

Neuhauser *et al.*, (1995) found that only Cd and Zn were bioconcentrated in earthworms. Increasing the voiding period increased the concentration of these metals in the worm-soil complex. Conversely, increasing the voiding period for metals that were not bioconcentrated (Cu, Pb and Ni) decreased metal concentrations in the worm-soil complex. Adding 2500 mg/kg Cu as copper sulphate to activated sludge killed all the *E. foetida* within one week (Hartenstein *et al.*, 1980). However, worms were not affected when feed non-amended sludge containing 1500 mg/kg Cu over several months.

Scarborough (2000) obtained mixed results on the changes in contaminant levels when vermicomposting biosolids and green wastes mixtures. After vermicomposting for 8 weeks, the following changes in metal content were found (Table 9). The increased concentration of some contaminants was thought to be due the reduced volume after composting.

Table 9: Changes in heavy metal concentrations when vermicomposting biosolids (BS) and green wastes (GW) for 8 weeks (from Scarborough, 1997).

Element	100% Biosolids		50% BS – 50% GW		35% BS – 65% GW	
(mg/kg)	Start	Finish	Start	Finish	Start	Finish
Cadmium	<2	2	<2	1	<2	<1
Copper	210	185	140	90	80	80
Zinc	390	320	270	220	145	210

After earthworms had been vermicomposting sewage sludge for three months, heavy metal accumulation in *E. fetida* was greatest for Cu (x 12), Pb (x 10), Cr (x 8), Zn (x 7.5), Ni (x 6), and Cd (x 4.5) (Saciragic *et al.*, 1990). However, only the iron content of the vermicasts increased (50%), while all other element concentrations decreased (Zn, 89%; Cu, 90%; Cr, 88%; Pb, 87%; Cd, 86%; and Ni, 51%). Commercial vermicomposting operations at Vermitech indicated that the digestive processes of worms and biological processes

sequestered heavy metal contaminants, binding them tightly within the organic fraction, and thus controlled their release to the soil (Patten, 2002).

3.2.3 Persistent organic polluntants

Sewage sludges can also contain organic pollutants, with dieldrin and organo-chlorides being of greatest concern. Concentrations will depend on the activities within the sludge catchment. Phenols and amines were the most toxic of the chemicals tested by Neuhauser et al., (1985), followed by substituted aromatics, halogenated aliphatics, polycyclic aromatic hydrocarbons, and phthalates. Edwards and Bater (1992) used two standardised tests (filter paper and artificial soil) and found that chloracetamide, chlordane, pentachlorophenol and carbaryl were the four most toxic chemicals (Table 10). These authors concluded that the artificial filter paper test was an effective and reproducible screening test and that the artificial soil test is best for making more realistic assessments of the actual potential hazard of chemicals to earthworms (used as indicator species for soil pollution).

Table 10: Toxicity of chemicals to *Eisenia fetida* tested with filter paper and artificial soil (from Edwards and Bater, 1992).
LC = lethal concentration; CL. = confidence limits.

	Filter paper test		Artificial soil test	
Chemical	LC50 (mg/kg)	95% CL. (mg/kg)	LC50 (mg/kg)	95% CL. (mg/kg)
Chloracetamide	3	1	39	20
Chlordane	4	3	75	48
Pentachlorophenol	7	4	69	32
Carbaryl	8	4	83	51
Copper sulphate	26	9	1105	377
Trichloroacetic acid	96	22	1140	423
Potassium bromide	453	209	298	178

3.2.4 Adverse factors

Most sewage sludges produced in wastewater treatment plants undergo anaerobic digestion and are toxic to *E. fetida* when fresh (Edwards, 1995). Even sun-dried anaerobic sludge is lethal to *E. fetida* when it is first moistened, and remains toxic for up to ten days despite daily watering; however after 14 days, toxicity disappeared. Aerobic sludges that were allowed to become anaerobic inhibited growth but were less toxic than the original sludge (Hartenstein, 1980).

Anaerobically-digested sludges have low oxidation-reduction potentials and are toxic to earthworms. If these sludges are placed on a soil substrate, their redox potential increased slowly and became non toxic at Eh values >250 mV. However, Kaplan et al., (1980) found they have insufficient nutrients to support *E. fetida* growth.

Edwards (1985) reported that the length of time since anaerobic sludges were removed from an anaerobic reactor and dewatered affected earthworm growth rates. The nutritive value of 12 week old sludge decreased rapidly after removal from digester, Neuhauser *et al.* (1980).

3.3 Sludge pre-treatment

Wastewater treatment plants design and operational procedures are not standard so highly variable sludges are produced. Dewatered biosolids cannot be feed directly to worms (David Fletcher, Vermitech, pers. comm.). A critical factor is minimizing the production of volatiles in any material used in vermicomposting because most gases associated with odour are toxic to worms (Lotzof, 2000). For example, hydrogen sulphide is toxic but can be prevented if conditions in the worm beds do not become anaerobic.

Most biosolids contain flocculants and polymer constituents, which are added during wastewater processing to increase solids content. Kaplan et al. (1980) reported that most inorganic chemicals used to coagulate sludges were innocuous at concentrations higher than those normally in wastewater treatment. Commercial vermiculture operations in Australia found that only alum (aluminium sulphate) sludge was unpalatable as a sole feedstock for worms (Vermitech, 1999).

3.4 Blending feeds

Cellulose is probably required for rapid growth of *E. fetida*. Sludges contain sufficient endogenous cellulose (from undecomposed toilet paper, undigested food fibres, and possibly microbial cellulose) which enables rapid growth of *E. fetida* (Hartenstein, 1980). However, the same study found that more *E. fetida* were produced on diets with 33-75% cellulose than on sludge only. While laboratory experiments by Morgan (1988) indicated that *E. fetida* could utilise both micro-organisms and simple nutrients, and grew very well on pure fungal cultures, especially *Arthrobotrys*. Hatanaka et al. (1983) reported that dairy sludge cake supported earthworm growth without prior composting and was superior to cow manure when supplemented with high cellulose materials such as rice straw or newspaper. Maximum *E. fetida* growth rates occurred using a 2:1 ratio (w/v) of paper tissue wastes and cattle slurry (Hand et al., 1988) and reproduction rates increased when fed higher amounts of slurry. *Eisenia fetida* biomass increases were found by Neuhauser et al., (1980) to be similar whether fed activated sludge or activated sludge mixed with either pure cellulose fibres (66-80% moisture) or newspaper strips (0.5 x 2.0 cm).

Biosolids and green (or vegetative) wastes each contribute about 25% to the Lismore, NSW, total organic waste stream. High quality vermicasts were produced when these wastes were blended (Ray O'Grady, Tryton Wastes, NSW, pers. comm.). Blending trials by Vermitech (1999) found that timing of mixing including the rate and sequence of blending were important factors given the variability of feedstocks including biosolids, shredded paper, green wastes, and powdered minerals. Vermicomposting experiments by Scarborough (2000) found that the optimum volume mix was 40-45% biosolids and 55-60% chipped green wastes. Biosolids mixed with 10% shredded green wastes are used as worm beds in a commercial operation in South-East Queensland (David Fletcher, Vermitech, pers. comm.). A commercial vermicomposting plant run in Newcastle, NSW processes about 25 m^3/week of a 1:1 mix of biosolids and vegetable residues (Appelhof et al., 1996). The Recycled Organics Unit in NSW found that the optimal proportions for vermicomposting were: 41% (w/w) fruit, 41% vegetables and 18% shredded cardboard (moisture absorbent bulking agent). This feedstock

was applied three times each week to give a weekly loading rate of 24 litres/m^2 or 16.5 kg/m^2 (ROU, 2002).

3.5 Feedstock quality control

It is important to monitor the affect of substrate on earthworm growth, reproduction and/or viability. Cuban vermicomposting centres test each batch of feedstock before using it to build windrows by placing 50 earthworms in a shallow box (15 x 30 x 7 cm) of the substrate. The materials are used if at least 48 earthworms survive for 24 hours (Werner and Cuevas, 1996).

3.6 Feed particle size

Particle size affects nutrient availability, probably because micro-organisms can access greater surface area per unit volume of waste material and potentially supply more food for the worms (Neuhauser et al., 1980a). Further investigations (Neuhauser et al., 1980b) found that *E. fetida* weight gain was inversely proportional to particle size of various feedstocks and that food particles >2 mm^2 supported growth. ROU (2002) recommended that all feedstock components be combined with smaller particles (<20mm in diameter) to increase surface area and allowing more through mixing. Mike Daniels (Australia Worm Growers Association, pers. comm.) considered homogenous mixing was very important to ensure consistent processing in organic material. The processing method can have an effect on particle size distribution of vermicasts and is discussed in Section 4.3.

Chapter 4 Vermicomposting systems

4.1 Bedding systems

Vermicomposting systems range from simple low-technology operations using windrows, heaps or boxes to complex, fully-automated continuous breeding systems. The system chosen depends on community requirements and land, labour and capital considerations. Many operations can be mechanised, but mechanisation costs must be balanced by labour and space savings.

Worm beds must be protected from rain, wind, and birds for successful operation (Wilson, 1999). Maximum productivity is achieved by maintaining optimal moisture and temperature under aerobic conditions (Edwards, 1988). The basic principle of breeding systems is to add small amounts of wastes frequently so the earthworms can process successive aerobic layers. Worms always concentrate in the upper 15cm of material and move upwards as further layers are added.

Windrow systems are commonly used and can be either outdoor, under cover or indoor but large areas of land or large buildings are needed. Windrows typically are less than 1 m high with thin (5-8 cm) layers of feedstock applied weekly to prevent heat build-up. Sherman (2002b) suggested that windrows should be less than 6 m apart so any worms migrating to adjacent windrows can do so safely. It is difficult to harvest castings from windrows without including the worms so mechanical harvesters are commonly used to separate worms from castings.

Because traditional vermiculture requires large land areas, bedding systems have been developed to reduce the 'footprint' which allows plants to be located near the waste source (Lotzof, 2000). The wedge system (Jim Jensen, Seattle, USA) is a modified windrow approach that reduces the space required and simplifies harvesting. A regular windrow is constructed by making a 0.3-0.5 m wide strip of manure or bedding and then gradually adding organic materials until the pile is 0.6-1.0 m high. The windrow is extended by applying successive layers at 45 degree angle against one side of the windrow until it is 0.6-1.0 m thick. More wedge-windrows can be added in the same way until the plant's capacity is

reached or there are space limitations. Worms do not have to be separated from the castings because they migrate laterally to the fresher feedstock. The first windrow will be ready to harvest after two to six months (Sherman, 2002b).

Beds and bins are commonly used in vermicomposting systems and are particularly suitable for smaller scale operations. Bins are popular if space is limited and have the advantage of being able to be stacked. Beds can be made from materials such as wood, brick, or corrugated iron and can be on-ground, off-ground or raised Wilson (1999).

Continuous flow systems are basically linear raised beds with sidewalls with a mesh floor to support the substrate which allows regular feeding on the top and periodic removal of castings from the bottom (Appelhof, 2003). These beds are 1.5-2.5 m wide, 20-30 m long and have a 5 x 5 cm mesh floor. The beds are lined with thin layers of newspaper to prevent substrate falling through mesh. A shallow layer of substrate is then placed on the paper and seeded with 4 kg of worms per m^2 of surface area. The worms settle in and begin consuming the substrate. As both top and bottom surfaces have access to airflow, anaerobic conditions are unlikely to develop. Continuous flow systems can be automated by either using tractor-mounted feeding to the top surface followed by raking in or using a feeding gantry system to apply even thin layers (1-5 cm) of feed. Haimi and Huhta (1986) found that biosolids should be applied in layers <5 cm deep but mixed organic wastes could be applied loosely in layers up to 10 cm thick. Various vermicomposting systems are summarised in Table 11.

Table 11: Vermicomposting systems (from Edwards, 1988).

Method	Comments
Windrows and beds	Labour intensive. Needs relatively large area of land. Seasonal activity unless covered.
Crates or boxes	Handling of units and watering difficult.
Moving belt system	High initial cost.
Continuous flow suspended beds	High initial cost, but economic to run due to low labour costs.
Trickling filter systems	Have excellent potential for liquid wastes but need further development.

4.2 Commercial vermicomposting systems

Sherman (2002b) described the following commercial vermicomposting systems:

1. Biosystem Solutions system

The BioSystem 500 is made up of modules 0.9 m long x 0.6 m wide x 1.2 m high, which can process 9 kg/day (Figure 3). They have an automated irrigation control system and leachate collection and can be assembled to handle up to 275 kg/day. Labour requirements are 20-60 minutes/day depending on feedstock volume. This company also has a harvester, which has a 3-4 m long screw auger that moves castings from the bottom of the windrow to the side (removing 8-30 cm from the bottom layer).

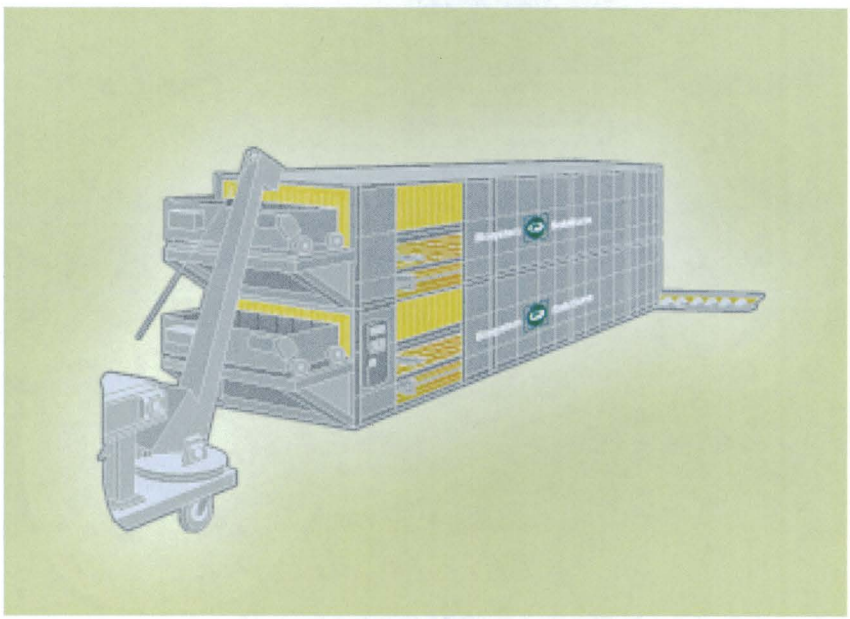

Figure 3: BioLane vermicomposting system, BioSystem Solutions, Fairfax, CA, USA

2. EPM Inc.system

The Worm Wigwam is an ideal system for hospitals, university cafeterias and centralised processing stations. The mid-size model has a steel frame with a raised grate and an insulated bed (1.5 m wide, 1.8 m long and 1.2 m high) (Figure 4). The grate has a hand crank operated breaker bar to separate the castings requiring approximately 1 hour/day for harvesting. About 45 kg of worms can process 35 kg of organic matter per day and produce 20 kg of castings.

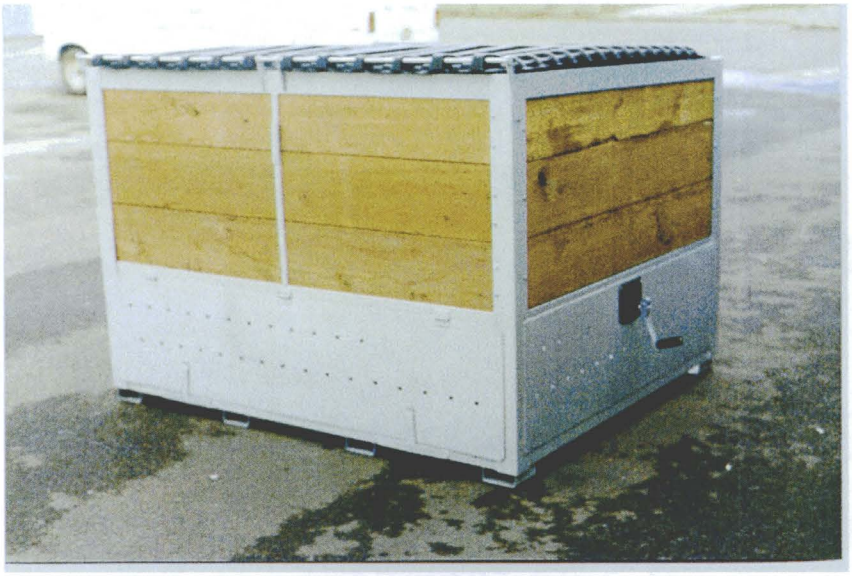

Figure 4: Worm Wigwam. EPM Inc., Cottage Grove, OR, USA.

3. Vermitechnology Unlimited System

Bins (4.8 m wide x 30 m long x 0.6 m high) with 3 m wide insulated panels are suspended 15 cm above a 10 cm concrete slab. A shade cloth or metal roof is installed 2 m above the bin and there is an automated sprinkler system. A castings extractor is attached to a three-point hitch on a tractor that sweeps the castings from the bottom onto a conveyor or pad. This system can process 1 tonne/day and requires about 2 hours of labour per day to feed and water.

4. Worm World, Inc system

This modular system, called the "Worm Gin" (Riggle, 1998), uses a stacked series of conveyor belts for worm beds (Figure 5). The stackable design allows beds to be placed vertically or horizontally into the space and therefore has a small 'footprint'. The standard model has 14 beds (5.4 m high with 28 beds of 4.5 m^2 each). A single module has two stacks of beds separated by a feeder. Feed is put into a hopper above the feeder and then mechanically distributed evenly over the worm beds. Daily processing rate is 5-15 kg/m^2 of bed per day with an overall processing time of 7 days followed by two to three weeks of curing. The beds are set on a concrete slab base and are made of plastic, stainless steel, aluminium and pressure-treated wood in the non-food contact area and turn slowly on rust-resistant bearings. As beds are thin, only 100 cm deep,

mesophyllic bacterial growth is aided because of increased aeration (Riggle, 1998).

Figure 5: Worm Gin plant in South Korea, Worm World, Inc., Gainesville, FL, USA.

5. Vermitech Systems

Various sized digesters can process 20-1350 kg/day. A mulching mixing processor, which can accept all compostable organics, feeds material into the digester. Temperature is controlled automatically with fans and air conditioning. Some models have manual or automated or misting systems and capacity can be increased by adding 2.4 m long modules. The units need about 3 hours of labour per day and use 70-80 litres of water daily. The company also manufactures shredders/mixers and harvesters.

Vermitech have a large scale commercial operation in Brisbane processing 250 m^3 of biosolids in a continuous flow process (Figure 6). The modular beds are 4 m wide, 0.7 m deep and 70 m long but can be configured to any length (Lotzof, 2000). The raised beds have galvanised steel frames and the waste and worm biomass are held within the meshed sides and base. Biosolids are homogenised with 10% shredded green waste and fed to the worm bed surface at 15-17 mm layers three times per week (David Fletcher, Vermitech, pers. comm.).

Figure 6: Continuous flow raised beds for large-scale vermicomposting operation (Vermitech Pty. Ltd., Redland, Qld, Australia).

4.3 Integrated systems

High quality compost takes about six months to produce but its nutritional value as worm feedstock drops rapidly because of microbial degradation so using vermistabilisation as a secondary treatment after conventional thermophilic composting was considered not feasible by Hartenstein et al., (1979). However, Riggle and Holmes (1994) reported a marketable product could be achieved in 30 days when organic materials underwent thermophilic composting for 3-15 days, to reduce pathogens and destroy weed seeds, before being vermiprocessed and converted to humus by worms.

Ndgewa and Thompson (2001) mixed biosolids (activated sludge) with paper mulch to give a C/N ratio of 25:1 before composting for 28 days followed by vermicomposting for the 28 days and vice versa. The combined composting/vermicomposting system shortened stabilisation time, achieved greater reduction in volatile solids (Table 12).

Table 12: Characteristics of feedstock and products after composting and vermicomposting (from Ndgewa and Thompson, 2001).

Processing system	N (%)	P (%)	VS (%)	pH
Original feedstock	1.71	0.70	82.1	7.55
Vermicompost	1.67	0.81	73.6	6.47
Vermicompost-compost	1.68	0.72	69.6	6.05
Compost-vermicompost	1.70	0.83	71.1	6.10

The compost/vermicompost systems also produced the finest and most homogenous products (Table 13). Although they did not present the data the authors also reported that total solids were reduced by around 45% in both combined systems compared to 35% for vermicomposting alone, which represents significant savings in handling and transport costs of final product. Frederickson *et al.*, (1997) also noted the importance of minimising the composting phase (to less than two weeks) to ensure maximum efficiency during the vermicomposting phase of an integrated operation.

Table 13: Effect of treatment on particle size distribution (% retained on sieves) (from Ndgewa and Thompson, 2001).

Sieve size (mm)	Original Feedstock	Vermicompost /compost	Vermicompost only	Compost/ Vermicompost
6.35	55.40	29.30	9.55	0.15
3.36	23.90	15.55	8.20	1.35
1.68	12.45	14.45	7.50	4.95
1.19	4.40	11.50	6.80	10.60
0.84	2.40	15.90	20.40	36.85
0.42	0.85	11.10	38.90	40.10
0.25	0.30	1.45	6.40	5.25
-	0.30	0.75	2.25	0.75
Mean Particle size	5.15 mm	2.53 mm	1.08 mm	**0.83 mm**

A Cuban vermiculture system uses cow manure as its primary feedstock, as well as pig and sheep manure, sugar cane pulp, coffee pulp, and other crop residues. The feedstock undergoes thermophilic composting in twice-weekly turned windrows for 15 to 30 days before being fed to the worms (Werner and Cuevas, 1996). Vermicomposting occurs in windrows with thin layers of feedstock being spread on the top. When the windrows are 65 cm high, worms are drawn to the surface with a fresh layer of food. Five to seven days later, the top 10 cm are skimmed from the windrow with a front-end loader, removing 80% of the worms. The worm harvest can be increased to 90-92% with a second feeding and loading pass. A mechanical harvester is used to separate the worms from their castings.

4.4 Worm stocking densities

Pike and Venkitachalam (2000) found that high stocking densities of adult *E. fetida* and inferior food quality caused worms to shrink. A stocking rate of 1:10 worms to wastes gave maximum biomass productivity for most organic wastes (Edwards, 1988). The quickest processing time for producing vermicasts was achieved by inoculating the wastes with nearly fully-grown earthworms.

Eisenia fetida produced cocoons 10 days after being transferred to dairy sludge cake feed, and hatchlings appeared at 30 days. Thereafter, on average, four progeny were produced from each adult worm every 5 days for 120 days, after which the rate declined (Hatanaka et al., 1983). The organic matter/ash ratio of the dairy sludge decreased from 4.5 to 2.1 after 120 days, which is similar to the ratio in natural composts (2.0). This ratio coincided with a decrease in their reproductive rate indicating that the worms should be transferred to fresh feed.

The feeding rate of *E. fetida* depends on nutritional quality of the substrate. When living on optimum substrates, such as activated sludge, Hartenstein (1981) found that worms ingest one-quarter of their body-weight daily. Worms eat more food when the nutritional value is lower as long as the substrate is not toxic (Neuhauser et al., 1980a; Hartenstein et al., 1981b).

The optimal worm stocking density was 1.60 kg worms/m^2 when feeding biosolids mixed with paper-mulch at 0.75 kg feed/kg worms per day (Ndegwa et

al., 1999). Cuban vermicomposting operations (Werner and Cuevas, 1996) use a stocking rate of 1 kg/m^2 to seed *E. andrei* into windrows 10-15 cm high.

4.5 Harvesting

Castings do not readily fall through the mesh at the bottom of continuous flow systems. The vermicompost tends to cake and these cakes needs to be prodded, agitated, or otherwise broken up so the worm castings can fall to the floor. Various mechanical breaker bars powered by winches, cables or chains can be used to slice off a measured portion of vermicompost, which then falls through the mesh gratings and is collected. Commercial operators have found the ideal mesh size to be 5 x 5 cm (Appelhof, 2003). Another harvesting system uses a low-level trolley travelling on rails under the raised beds. The beaker bar agitates the bottom of the bins and the vermicasts drop into the trolley (Ray O'Grady, Tryton Wastes, pers. comm.). Biomass harvesting rates of 20 tonnes per hour have been achieved from fully stable beds in commercial operations (Vermitech, 1999).

Chapter 5 Vermicomposting process

5.1 Starting the vermicomposting process

Dr Scott Subler's observed that many people start out with an unsuitable material for worms to live in, "it takes time for worms to get used to a new environment, but if added with their castings they can withdraw into it if the manure is noxious to them" (Sherman, 2002a). To start his 65 m^3 reactor, Subler adds a substrate of 20 tonnes of worm castings over newspapers then waits one week before adding worms in more castings. After allowing a further two weeks for the worms to settle in, three tonnes of dairy manure are added. Further two to three-tonne manure applications are added each week. The rate of manure application is adjusted simply by watching the bed and adding more when the worms have consumed the substrate (Sherman, 2002a).

Herlihy (2001) illustrated a conceptual floor plan of a vermicomposting plant (Figure 7) and a flow diagram of the production process (Figure 8).

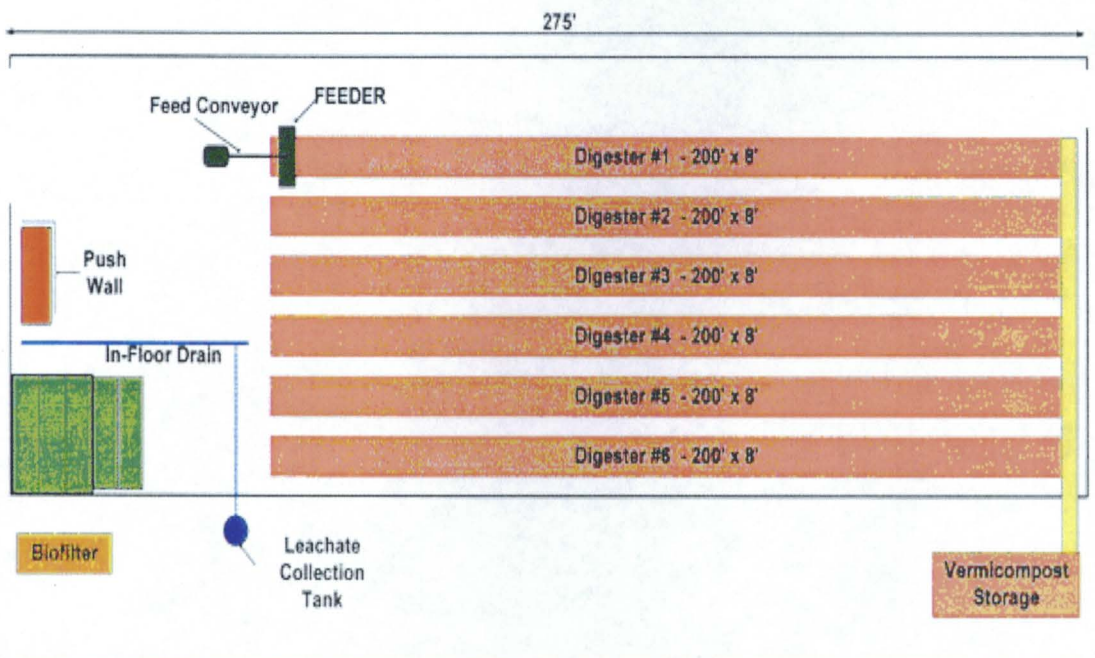

Figure 7: Conceptual floor plan of vermicomposting (from Herlihy, 2001).

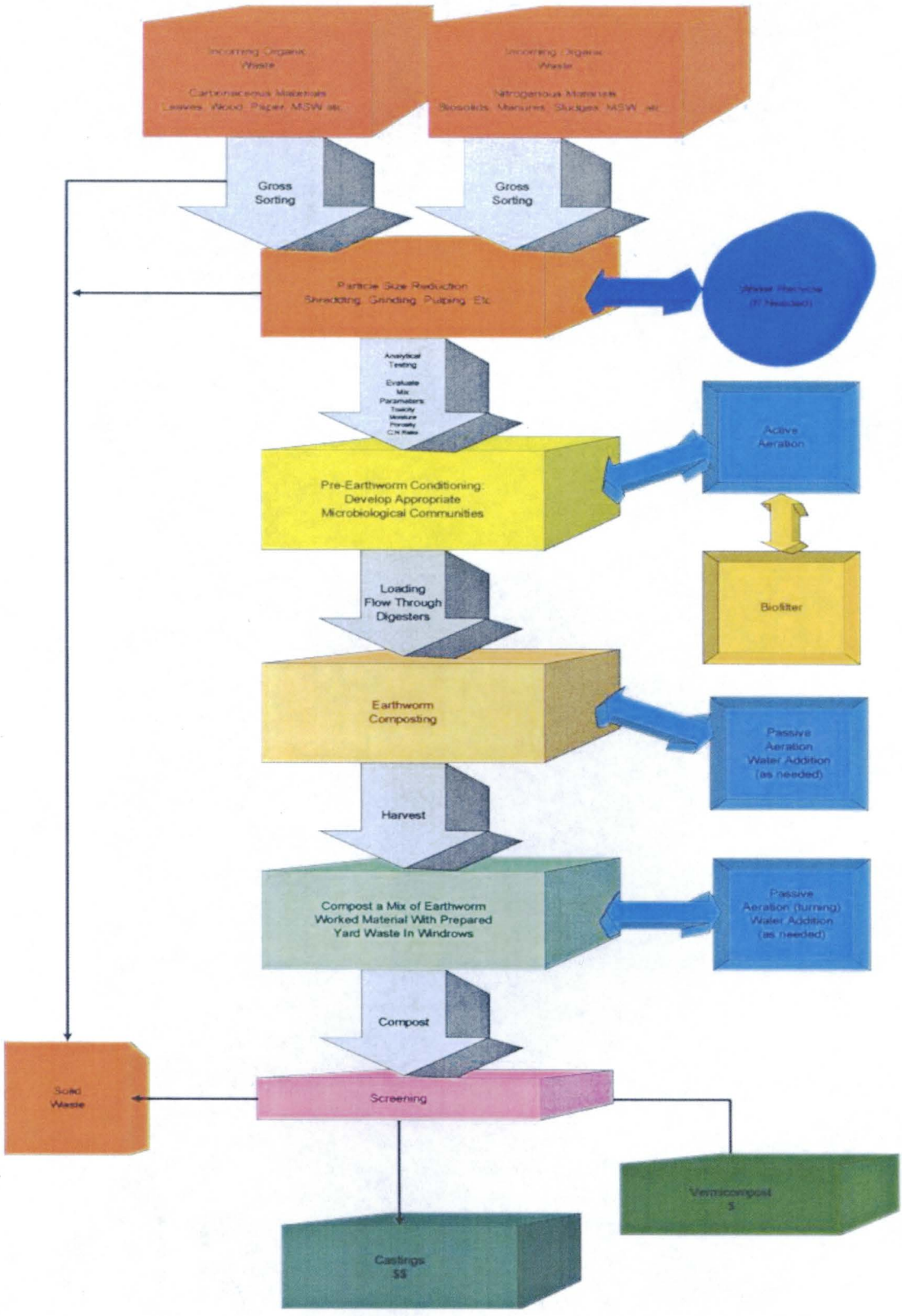

Figure 8: Flow diagram of vermicomposting production process (from Herlihy, 2001)

Details of individual processes of a vermicomposting plant processing biosolids and observations are necessary for major vermicomposting operations (Figures 9-12):

- Collection and mixing: Dewatered biosolids are fed into a mixing hopper together with a carbonaceous bulking agent such as sawdust, leaves, or newspaper. Load cells on the loader help weigh an appropriate "mix" such as four parts biosolids to one part sawdust. The mixer grinds and homogenises the feedstock, producing a material that can support a large population of microorganisms.
- Pre-conditioning: The mixed material is composted in a conditioning bay for a minimum of three days (to achieve thermophilic temperatures).
- Loading and feed distribution: Mixed composted material is placed in a hopper above the feed conveyor (Figure 9). The feeder (a modified manure spreader) is mounted on rails on the digester sides and discharges 25-50 mm thick layers of feed as it moves along above the digester. A transfer cart transfers the feeder between digesters (Figure 10).
- Digester: The digester has plywood or mesh sides and a metal screen mesh base. It is supported by a strong metal framework 60 cm above the floor.
- Harvesting and collection: Worm-processed material is removed from the lowest part of the digester with a scraper bar above the mesh screen The scraper bar forces the bottom 25 mm of vermicompost through the bottom mesh screen (Figure 11) and onto the floor. A set of hydraulic paddles collects and pushes the material to the far end of the digester (Figure 12).
- Storage: The material is transferred by skid loader to temporary storage in a covered area and allowed to air dry for several weeks.
- Screening: Stored material is screened into three fractions:
    a) Over-sized particles (>12 mm) are returned to feed mixer for re-processing.
    b) Vermicompost – material between 5-12 mm.
    c) Castings – material <5 mm, which is marketed as pure worm castings.

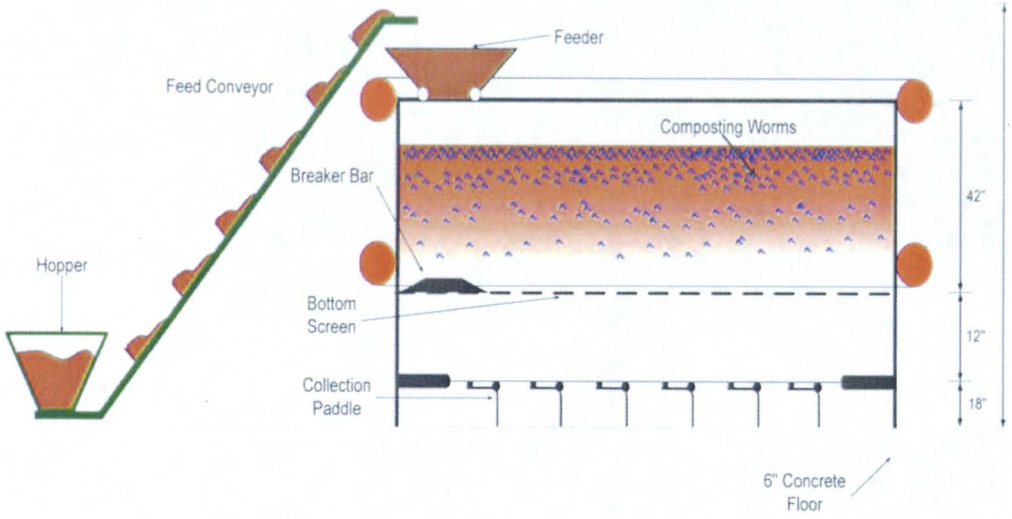

Figure 9: Loading the feeder (from Herlihy, 2001).

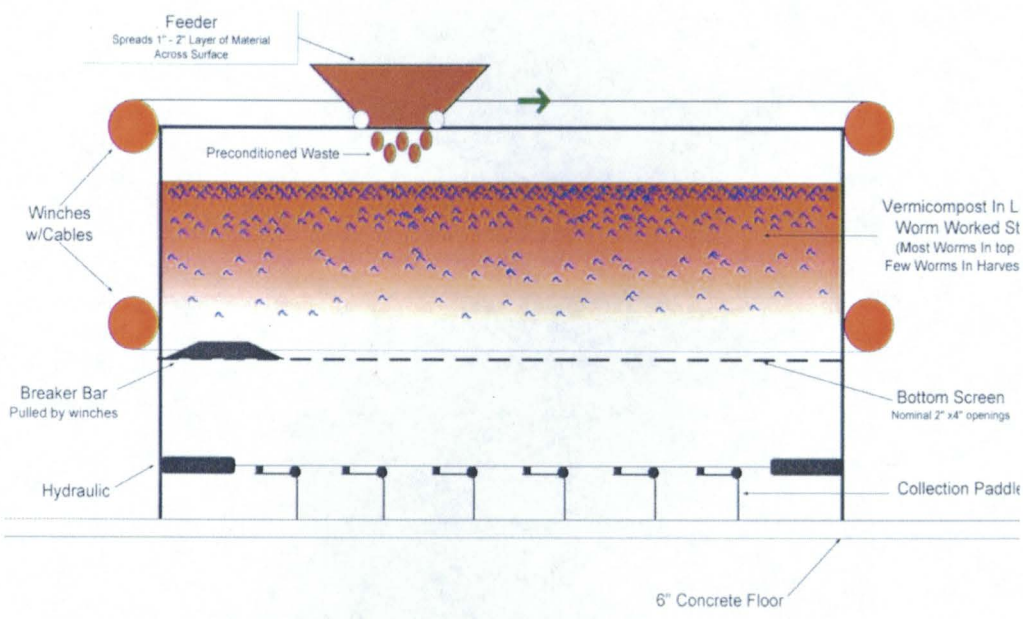

Figure 10: Feeding the worm beds (from Herlihy, 2001).

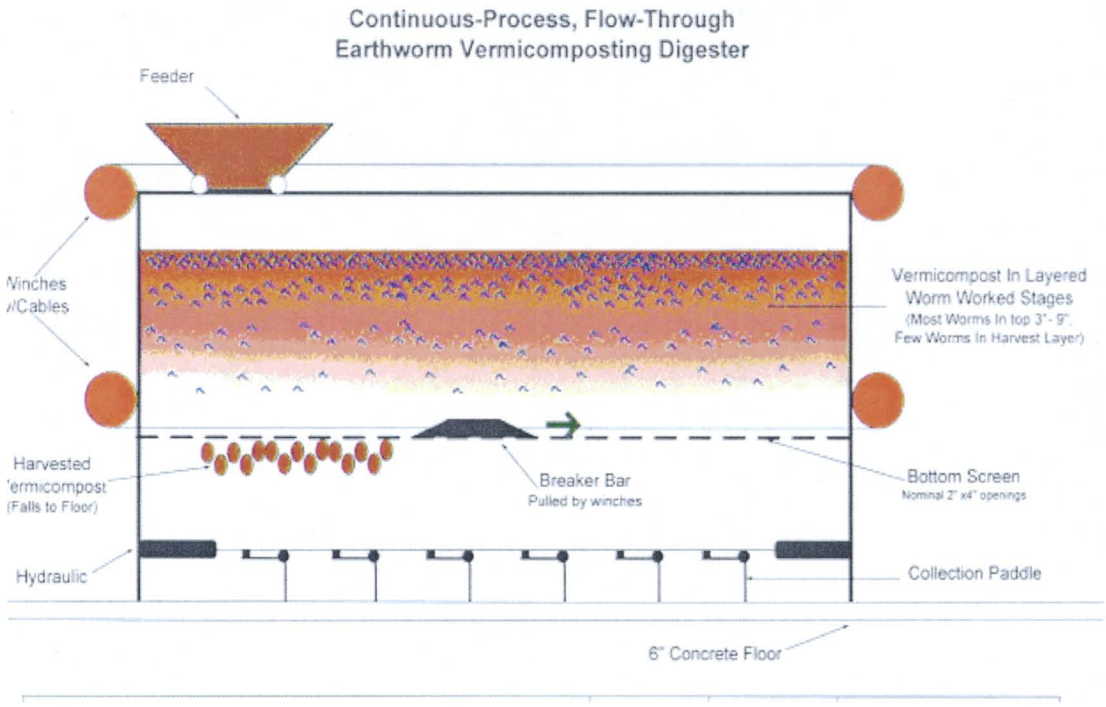

Figure 11: Worm activity within continuous flow digester (from Herlihy, 2001).

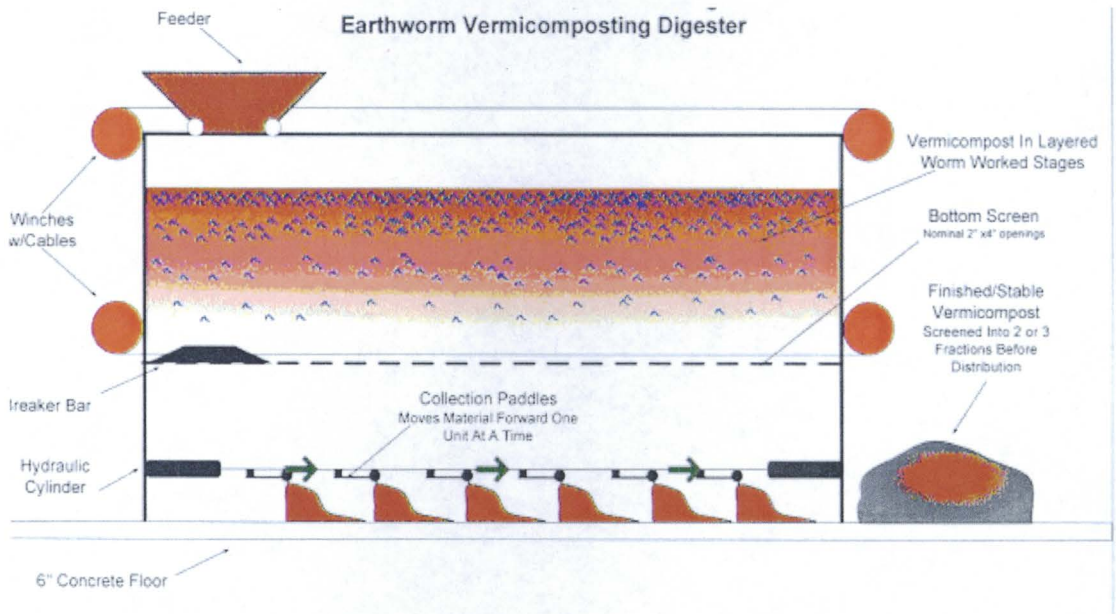

Figure 12: Collection of vermicasts from under digester (from Herlihy, 2001).

5.2 Worm bed troubleshooting

Normal worm husbandry practice requires constant observation of the worm beds. Wilson (1999) recommends a sniff test because worms, like any other creature, have their own smell and any state of distress can be quickly established by the intensity of their odour. Observing worm behaviour and making an assessment of their environment in response to any smell of stress is important and he lists four levels of odour:

1 Healthy – the normal smell of worms in a healthy environment is earthy with a hint of worm.

2 Distinctly wormy smell – their scent overpowers the medium they are in. The worms are still active but may exhibit signs of 'survival mode' (balling up or looking for an escape route). Worms still maintain their outer moist layer but are losing condition but body weight can be revived if correct moisture level restored.

3 Dying – high level of distress, worms have pungent, acrid, clinging, absorbing smell. Worms cannot maintain outer moist layer, have lost condition and may exude a yellow-green like oil. Immersion in cool water may revive some.

4 Dead – totally gagging and overpowering smell. Once smelt, never forgotten.

Several problems may be experienced within worm beds. One common cause is through over feeding and poor watering where a layer of fermenting and sour foods occurs in excess of the worms' ability to consume. The result is an accumulation of poisonous gases that can also dissolve and leach down through the bed (Wilson, 1999). The following worm troubleshooting guide (Table 14) can be used to identify common problems and their possible solution in a vermicomposting operation.

Table 14: Worm bed troubleshooting (from Sherman, 2000)

Problems	Causes	Solutions
Bed smells bad	Overfeeding	Stop feeding for two weeks
	Food scraps exposed	Bury food completely
	Bin too wet	Mix in dry bedding; leave lid off
	Not enough air	Fluff bedding; drill holes in bin
Bed attracts flies	Food scraps exposed	Bury food completely
	Rotten food	Cover with bedding
	Too much food; especially citrus	Don't overfeed worms
	Bin too wet	Mix in dry bedding; leave lid off
	Bin too dry	Thoroughly dampen bedding
Worms are dying	Extreme temperatures	Move bin to where temperature is between 13 and 25 degrees C
	Not enough air	Fluff bedding; drill holes in bins
	Not enough food	Add more bedding and food
Mould forming	Conditions too acidic	Cut back on citrus fruits
Bedding drying out	Too much ventilation	Dampen bedding; keep lid on
Water collecting in bottom	Poor ventilation	Leave lid off for a couple of days; add dry bedding
	Too many watery scraps	Cut back on coffee grounds and scraps with high water content
Worms crawling away (very rare)	Bin conditions not right	See solutions above.
		Leave lid off and worms will burrow back into bedding
	Excess vibration	Eliminate vibrations

5.3 Mass balance

To understand vermicomposting performance, it is necessary to understand the process dynamics due to changes in moisture content and volume of waste materials. Even experienced vermicomposting operators such as Tryton Wastes Ltd, NSW, can have difficulties obtaining quantitative mass balances on their operations (Ray O'Grady, pers. comm.). For example, 1 tonne of kerbside organic waste with 55% moisture undergoes about a 60% reduction in volume during composting. When fed to worms it has 80% moisture and produces 0.5 tonnes of vermicasts. Because of the magnitude of their operation, the mass balance through the plant has a major impact on its economic performance (Ray O'Grady, pers. comm.).

A flowchart from At Source Organics (ASO) Western Australian integrated composting/vermicomposting operation (Figure 13) indicates that 5-tonnes of biosolids and organic wastes lose 50% of their weight after composting. Screening the compost produces 67% coarse compost and 33% fine compost. The fines were then processed by worms into 0.42 tonnes of worm castings.

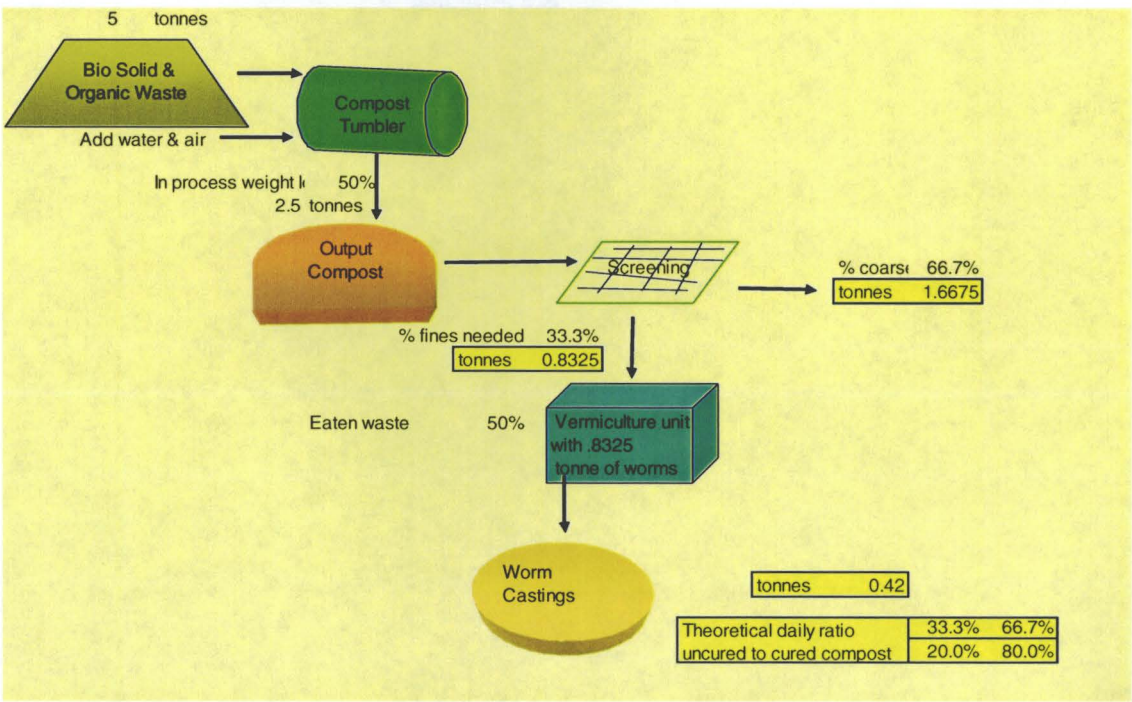

Figure 13: Mass balance of 5-tonne At Source Organics (ASO) integrated composting/vermicomposting operation (Walker, 2001).

Chapter 6 Worm-processed materials

Worm worked materials are a mixture of vermicompost and worm castings (Herlihy, 2001). Researchers around the world have investigated the agronomic benefits of using vermicasts.

6.1 Adding vermicasts to plant growth media

Vermicasts contain large numbers of micro-organisms and are much more microbially active than the original material. They do not need further curing and can be a better plant growth medium than either traditional compost or commercial growth media. This improved performance is thought to be due to greater availability of micronutrients, the presence of plant growth regulators and the effect of beneficial micro-organisms (D'Alton, 2002). Experiments at Rothamsted (Edwards *et al.*, 1980) showed that earthworms, especially *E. fetida*, break down organic wastes into peat-like materials rich in available nutrients with a good moisture-holding capacity and porosity.

Vermicasts appear to work best at 10-20% of the mix (Subler *et al.*, 1998, D'Alton, 2002). Higher levels do not always improve plant growth but additions as little as 5% can give a dramatic response in plant growth (Subler *et al.*, 1998). New Zealand research supports these findings. A glasshouse trial evaluating the effect of two vermicomposts showed that maximum oat plant growth was obtained when vegetable or pig vermicomposts were mixed with sand at 20% and 30% (by volume) respectively (Trish Fraser, Crop and Food, pers. comm.).

6.2 Chemical characteristics

Research (Werner and Cuevas, 1996) has shown that the feedstock influences the mineral content of vermicasts, particularly the major elements: phosphorus and potassium (Table 15). Chemical analysis of composts and vermicomposts by Subler et al. (1998) found that vermicasts tended to have a slightly higher nutrient content. In particular, vermicasts had lower ammonium-N levels but higher nitrate-N concentrations which was opposite to that found for composts.

Table 15: Effect of feedstock on the chemical composition (% fresh weight) of vermicasts (from Werner and Cuevas, 1996).

Feedstock	N	P	K	Ca	Mg	OM
Cow manure	1.70	0.62	1.22	10.0	1.53	44.5
Pig manure	1.89	1.50	0.34	10.8	1.46	44.0
Sheep manure	1.51	0.64	0.78	4.40	1.37	37.5
Sugar cane pulp	2.67	2.11	0.40	4.08	1.89	68.5
Coffee pulp	2.01	0.27	2.14	1.96	0.37	53.8
Banana	2.50	0.56	3.74	2.36	1.50	65.5
Ruminal contents	1.68	0.62	1.21	9.80	1.58	46.5
Urban/domestic	0.90	0.44	3.60	3.60	3.10	26.5
Typical analysis of feedstock	1.5 -2.2	0.8 -1.0	0.8 -1.2	4.70	0.30	65 -70

Werner and Cuevas (1996) also reported the vermicasts had 0.5 mg/kg copper, 150-170 mg/kg zinc, 500 mg/kg manganese, a carbon content between 13.1-17.3%, a C/N ratio of 10-11, and an average moisture content of 62%.

6.3 Markets

There are several outlets for products from vermicomposting. Solid vermicasts can be screened to produce fine (<10 mm) and coarse (>10 mm) fractions for different applications. Vermitech (Brisbane) supply their finer product for golf courses greens while the horticulturalists use the coarser product (David Fletcher, Vermitech, pers. comm.) Tryton Wastes (NSW) convert their vermicasts into a range of liquid products including 'Tryton VHE' (vermi-humic extract), which is a base for a range of concentrated NPK liquid fertilisers, and 'Tryton BioStarter', which contains enhanced bacterial or fungal populations and can be a standalone product or used with other products. The solid compost and vermicast products are marketed as 'Nature Cast' and used to enhance the beneficial microbial communities and complex biological interactions within soil profiles. 'Biostart cake', the solid product from finely sieved vermicasts, can be used as a spore carrying medium (e.g. for *Tracyderma* sp). Tryton Wastes is developing new products using the analytical services of the Soil Foodweb Institute (Ghani et al., 2002).

Chapter 7 Vermicomposting operations

7.1 Operations Worldwide

Vermicomposting has been widely adopted as a waste management solution in many countries around the world. For example, a 600-700 cow feedlot in Argentina vermicomposts 4.6 tonnes of dung daily (Schuldt *et al.*, 1999). Five different population stages of *E. fetida* were distinguished: empty cocoons; cocoons with content; translucid or low pigmented juvenile specimens; conspicuously red pigmented, sub adult worms, unclitelated; and adult specimens. Worm population was monitored over one year from an initial *E. fetida* density of 10,125 worms per 2-m^2 bed. The highest numbers were in the youngest feedlot casts and consisted of 280,000 worms 45-90 days old, 107,000 one-year old worms, and 58,000 two-year old worms. Feedlot casts were consumed in 90 days and the reproduction rates fluctuated between 2.3 and 7.3 times the initial number. Feed consumption increased from the initial 17 t/month to 104 t/month after one year, producing 57 t/month of worm casts. Fecundity of *E. fetida* was between 2.7-3.0 embryos/cocoon.

Appelhof *et al.*, (1996) describes the operation of a vermicomposting plant run by the Hobart City Council in Tasmania, Australia. The worms digest 50 m^3/week of mixed municipal biosolids/green mulch (to give a C/N ratio of 20-30:1). Zeolite is mixed in to help balance pH, and absorb ammonia and odours. Around 38 m^3/week of vermicasts are produced.

The Grace Kellar Centre vermicomposts about 10m^3/week of kitchen scraps, shredded paper, and garden trimmings at a hospital in Geelong, Victoria, Australia. Zeolite and soil is added to control pH and odour (Appelhof et al., 1996). This plant won a "Keep Australia Beautiful" award for rural town recycling and waste minimisation.

Another Australian company, PAD Engineering in South Australia, build and operate continuous flow digesters called 'Organic Bio Converters', which handle mixed waste streams such as yard trimmings, manures, papers, cardboard, and fruit/vegetable wastes. This facility use four 45-m long by 3.6-m wide vermiculture units, each with over 8,000 kg of earthworms, to process 18 m^3/day

of organic residue. After a 40-day vermiculture processing cycle, automated "harvesters" extract the material, which is then sieved, graded, and marketed (Biocycle, 2002b).

Spanish researchers found that adding manures or biosolids to solid paper pulp mill sludge produces an ideal worm growth medium (*Eisenia andrei*), which is then transformed into a useful organic amendment (Elvira *et al.*, 1997). The paper sludge is fibrous (70% crude fibre), has 80-85% moisture, a pH of 9.0-9.5, an electrical conductivity of 0.32 dS/m, and a C/N ratio of 257:1. The following paper sludge to manures ratios were used: rabbit, 5:1; biosolids, 4:1; poultry slurry, 4:1; and pig slurry, 5:1.

Vermicomposting is widely practised in Cuba, where vermicasts have become a substitute for imported agricultural fertilisers. There are over 170 vermicomposting operations, primarily using cow manure, although pig and sheep manure, coffee pulp, sugar cane pulp, other crop residues, and garbage are increasingly used as feedstocks (Werner and Cuevas, 1996).

7.2 Research worldwide

Laboratory and field research studies relating to vermicomposting have been conducted around the world (Table 14). Small scale laboratory studies have investigated growth rates and reproduction under different environmental conditions while larger outdoor experiments have measured pathogen reduction, stocking densities and biomass production.

7.3 Research in New Zealand

Two studies have been conducted in New Zealand since 1999. Rodney District Council investigated bedding systems, effective bulking agents, pathogen reduction, heavy metal concentrations, fate of synthetic organics and processing time for vermistabilising sewage sludge from the Warkworth Sewage Treatment Plant. The reduction in faecal coliform was disappointing and pre-composting before vermistabilisation was recommended to achieve required standards. Earthworm activity reduced concentrations of some heavy metals (Zn, Cd, Cu,

and Pb). However, the study by Naidu (2003) found that mercury levels (from dental discharges) should be closely monitored and controlled by council trade waste officials. Green wastes from parks and reserves (used as bulking agents) contained unacceptable levels of Dieldrin (used as a pesticide) and also needed monitoring by Council. The overall findings demonstrated that vermicomposting could be used as a polishing treatment for composting (Naidu, 2003).

The other study by Crop and Food investigated plant growth from two vermicasts as previously mentioned in 6.1.

Table 16: Vermicomposting research studies.

Site	Feedstock	Container	Feed rate	Worm rate	Objective	Reference
Lab UK	Cow slurry/ bedding materials (40% solids)	Petri dishes: 100 x 5 cm	100 g	5 juveniles	Reproduction 35 days	Hand *et al.*, 1988
Lab UK	Cattle wastes	Dishes: 7 x 4 cm	30 g	5 hatchlings (20 mg)	Production	Morgan, 1988
Growth chambers Japan	Dairy waste sludge cake (15% solids)	Plastic boxes; 230 x 135 x 60 cm		20 worms av. wt. 1.33 g	Biomass production 70-120 days	Hatanaka *et al.*, 1983
Growth chambers Japan	Dairy waste / cellulose (5%)	Plastic boxes; 230 x 135 x 60 cm Petri + wet filter paper		5 hatchlings 16 cocoons	Growth rates Growth rates 70 days	Hatanaka *et al.*, 1983
Bench-top Australia	Vegetable wastes /coco-peat bricks, later sheep manure	Plastic containers: 100 ml	Ad Lib	2-25	Weight gain	Pike and Venkitachalam, 2000
Bench-top Australia	Fruit/Veg /cardboard Mixed food organics/cardboard	Plastic bins: 0.92 x 0.58 x 0.46 m	30 L/m^2 per week 15 L/m^2 per week	14.9 kg/m^2 16.8 kg/m^2	Processing time	ROU, 2002
Lab South Africa	Feedlot cattle manure (2-3 months old)	Glass flasks	10g x 10 days	10 x 25-day old worms	Biomass production	Reinecke and Viljoen, 1990
Lab South Africa	Cattle gut contents ex Abattoir	Glass flasks	10g x 10 days	12 x day-old worms	Biomass production	Reinecke and Viljoen, 1991
Lab South Africa	Cattle manure, dried and ground 25% solids	Plastic containers: 150 ml	10g + 5g per week	2 hatchlings	Reproductive studies 114 days	Meyer and Bouwman, 1997
Lab South Africa	Cattle manure, dried and ground, re-wetted to 25% solids	Plastic containers: 140 cm^2 surface area with fine gauze lids	200 g wet substrate + 30 g manure/week	10	Heavy metal effect on reproduction	Reinecke and Reinecke, 1997
Lab Spain	Pig manure/maple leaf (85/15 ratio)	Plastic dishes: 250 ml	100 g 150 g	4 (<100 mg lwt) 1-16 worms	Stocking rates 44 days	Dominguez and Edwards, 1997
Lab Spain	Paper-pulp w/w sludge (19% solids), biosolids, pig and poultry slurry	Plastic flask: 600 ml	100 g mixtures (wet weight)	1	Growth rates 42-106 days	Elvira *et al.*, 1997
Lab France	Horse manure and aerobic paper sludge (both 22% solids)	Plastic cylinders: 0.5 L for 0-42 days 0.9 L for 42-189 days	4-5 cm peat bedding 50 mg DM PS 100 mg DM HM/PS per g fresh worm/day	5 hatchlings	Growth rates 0-189 days	Fayolle *et al.*, 1997

Table 16: Vermicomposting research studies....continued.

Site	Feedstock	Container	Feed rate	Worm rate	Objective	Reference
Outdoor Portugal	Raw aerobic sludge /sawdust	Beds: 2.0 x 1.8 x 0.8 m Length Width Height	1:1, 1:2, 2:1 (vol) sludge/sawdust	1 kg/m^2	Pathogen reduction	Ressetti *et al*, 1999
Outdoor Australia	Biosolids/green wastes	Beds: 2.0 x 1 x 0.45 m			Optimum mixes and rates	Scarborough, 2000
Field South Africa	Sewage sludge (15-20% solids)	Windrows: 6.0 x 1.5 x 0.2 m	1,360 kg	1:1.5 worms /sewage sludge	Pathogen reduction	Reinecke and Viljoen, 1990
Outdoor USA	Biosolids/paper mulch (4:3 parts – wet wt.)	Bins: 0.21m^2 surface 0.56 x 0.38 x 0.25 m	0.75, 1.0 and 1.25 kg /kg worm/day	0.8, 1.2, 1.6, and 2.0 kg/worms/m^2	Stocking density	Ndegwa et al., 2000
Outdoor Finland	Mixed organic wastes	Beds: 2.0 x 0.4 x 0.2 m	3.6 kgs x 2 weeks	0.2 kg (800 worms)	Biomass 240 days	Huhta and Haimi, 1988
Outdoor Australia	Feedlot cattle manure (51% solids)	Bedding systems (3): 1.5 x 1.5 x 0.2 m	Vertical 0.225 m^3 Horizontal 0.09 m^3	1.125 to 2.813 kg	Production from 3 bedding systems	Mitchell, 1997
Lab USA	Activated sludge (12% solids)	Petri dishes: 20 x 100 and 60 x 15	30-50g + 12ml water 5g + 1.5ml water	1-4 2	Biomass $prod^n$. 56 d Biomass $prod^n$. 28 d	Hartenstein, 1983
Lab USA	Digested sludge (12% solids)	Petri dishes: 20 x 100 20 x 100 (10 reps) 300 cc dishes	70 g re-fed x 2 weeks 100 g 200-500 g	4 juveniles (<10 mg) 2 4	Growth rates 28 days Sludge age 28 days Sludge age 70-140 d	Neuhauser, 1988
Lab USA	Digested sludge (12% solids)	Petri dishes: 20 x 100 mm	70 g re-fed x 2 days	10 juveniles	Maximum liveweight over 36 days	Neuhauser, 1988
Lab USA	Dewatered activated sludge (20% solids)	Petri dishes: 40 x 100 mm	4 g	1g worms	Physicochemical changes	Hartenstein and Hartenstein, 1981
Lab USA	Digested sludge (conc. to 11% solids)	Tray: 23 x 18 cm	30 parts sludge (wet weight)	1part worms	Mineralisation rates over 4 weeks	Hartenstein and Hartenstein, 1981
Lab UK	Shredded green wastes (34% solids)	Pots: 0.5 litres (5 reps)	200 g	1-8 worms (30-40 mg)	Stabilisation efficiency 16 weeks	Frederickson *et al*., 1997
Lab UK	Aerobic / anaerobic Digested cattle manure (15% solids)	Pots: 10.5 cm diameter	60 g x 10 reps	4	Worm growth 49 days	Frederickson and Knight, 1988

Chapter 8 Current Research

8.1 Areas of investigation

Modern societies face two important problems: disposing of wastes and providing humus to help maintain fertility in intensively cultivated soils. Organic matter contains two essential components: carbon and humus. Humus is the completely decomposed remains of plants and animals and is essential for fertile soils. Carbon (the 'molecule of life') can be used to indicate the organic matter in the soil. Large decreases in carbon have been measured in heavily cultivated land in New Zealand (MfE, 1997).

Biosolids, and treated sewage sludge from wastewater plants could be used to restore denuded soils. Biosolids have high organic matter content and land application is becoming an increasingly attractive option if their limitations of odour and pathogens content can be removed. The following four areas were studied during the year to investigate the beneficial reuse of biosolids:

- **Characterising** the physical, chemical, and microbiological properties of biosolids and sewage sludges
- **Laboratory** investigations on **preference studies** to see whether and when worms would accept fresh biosolids and sewage sludges
- **Assessing** the effectiveness of **vermicomposting** to improve the physical, chemical and biological attributes of biosolids
- A **glasshouse study** to evaluate the effectiveness of the vermicasts produced from the biosolids.

8.2 Materials and Methods

8.2.1 Characterising biosolids and sewage sludges

Biosolids: De-watered anaerobically digested (AD) samples were collected from wastewater treatment plants in Taupo, Hamilton and North Shore. These plants service populations ranging from 30,000-180,000 people.

Sewage sludge: Samples were collected from stabilisation basins of smaller Waikato communities at Temple View, Huntly, Ngaruawahia and Te Awamutu. These plants service populations ranging from 800-8,000 people.

Physical measurements: Total solids (TS) were determined by oven-drying 50-150 g samples at 105°C and then burning the volatile solids (VS) in a muffle furnace at 550°C so only mineral ash remained.

Chemical measurements: The commercial laboratory, E-Lab at the Ruakura Research Centre, Hamilton, used standard methods to determine the major elements nitrogen, phosphorus, potassium, sulphur and organic carbon and the trace elements/heavy metals copper and zinc in the biosolids and vermicasts.

Pathogens: The most probable number (MPN) index was used to measure faecal coliforms and *Escherichia coli* (indicators of faecal pathogens) in the biosolids and vermicasts. Samples from the preference and vermicomposting studies were analysed at Bio Test Laboratories, Hamilton, using standard methods (APHA, 1998). Because of the greater number of samples from the glasshouse trial, total coliforms, faecal coliforms and *E. coli* populations were measured by AgResearch microbiologist, Upali Sarathchandra, using the MPN method described by Turco (1994).

8.2.2 Preference studies

Worms: Eisenia fetida, also known as the tiger or compost worm, were sourced from local worm farms. These are the most common species used in vermicomposting in temperate countries.

- Study 1: This was done to determine how long before worms would tolerate biosolids, given no other substrate. Worms were put into identical containers with no bedding material. Any worms that perished were removed and a fresh batch introduced after two days. The time for the worms to accept and start processing the biosolids was recorded.

- Study 2: This was done to observe worm behaviour. Five juvenile worms with approximately 50 g of stabilised bedding material separated from the biosolids were introduced to 100-250 g of biosolids in 2-L containers. The time taken for the worms to migrate from the bedding (which although habitable had very little nutritional value) to the biosolids was observed and numbers recorded.

8.2.3 Vermicomposting sewage sludge

About 50 worms were seeded into 1-1.5 kg (wet weight) of the three AD biosolids and the Te Awamutu sewage sludge and left for 30 days to produce vermicasts. The physical, chemical, and microbial changes in the vermicasts were characterised and differences from the original biosolids used to indicate the degree of stabilisation and pathogen reduction. Vermicasts produced in this study were then used for the glasshouse trials.

8.2.4 Glasshouse trial

Cropping soil: Otorohanga silt loam (a volcanic ash soil) was collected from a South Waikato farm that had been growing maize continuously for 28 years. The physical and chemical characteristics are presented in Table 17. The soil had 2 ug/g (wet wt) ammonium-N and 39 ug/g (wet wt) nitrate-N.

Table 17: Some physical and chemical properties of the cropping soil used.

Bulk density (gm/ml)	pH	Olsen P (µg/ml)	Organic carbon (%)	Organic Matter (%)	Total Nitrogen (%)	Sulphate sulphur (ppm)
0.64	6.1	26	5.2	8.9	0.46	134

A weighed amount of vermicasts were well mixed into a measured amount of freshly collected soil and placed in 150 plastic pots (400g volume). The vermicast amounts were determined by their N concentration to give an application rate of either 250 or 500 kg N/ha. The weight of wet vermicasts to give 500 kg N/ha rate per pot was 56, 46, 62, and 112 g of North Shore, Hamilton,

Taupo, and Te Awamutu material, respectively. Vermicasts were added at a higher rate than normally applied to cropping soils to give a sufficiently high population of faecal coliforms at the start of the experiment and make it easier to monitor their persistence in the soil-plant system.

After filling the pots with the growing medium, three ryegrass (*Lolium perenne*, cultivar 'Samson') seeds were planted in each. Moisture and temperatures within the glasshouse were computer-controlled and optimised for plant growth (Figure 14). Pots were watered regularly every 2-3 days, and once a week, water was added to represent 75% of soil's field capacity.

Figure 14: Randomised block of pots in glasshouse trial.

8.2.5 Measurements

Three pots from each treatment were destructively sampled 24, 42, 56, 76, and 90 days after adding the vermicasts. Shoot growth 5 mm above the soil surface was harvested and oven dried at 70°C overnight to determine dry weights (DW). Soil was removed from the pots and root mass separated from the growing medium. Root mass was washed to remove adhering soil, oven-dried overnight at

70°C and root DW recorded. If shoot growth in pots to be destructively at a later date reached 18-20 cm, it was trimmed at 25 mm above soil level and dried. This ensured that regrowth could occur and that plants would remain in an optimum growth phase. Immediately after each destructive sampling representative soil samples (~30 g) were collected to determine total coliforms, faecal coliforms and *E. coli* concentrations.

8.2.6 Statistical analysis

Dry matter yields, chemical analysis, and indicator pathogen numbers were subjected to analysis of variance. Means and their least significant differences (LSD) at 5% level were calculated to determine statistical significance. Where appropriate, some data sets were log transformed. In this case, back-transformed means and the least significant ratio (LSR) at 5% level are presented.

8.3 Results and Discussion

8.3.1 Characteristics of biosolids and sewage sludges

The fresh biosolids had 17-27% total solids (74-83% moisture) (Table 18), which is within the optimum moisture range of 80-85% for worms (Edwards, 1988). This moisture content and the high carbon and volatile solid values of the biosolids indicated they would be suitable substrates for vermicomposting.

The sewage sludges had very high water content (Table 18) and would benefit from being de-watered or blended with cellulose materials such as paper or cardboard. Sludges from both Huntly and Ngaruawahia had very low volatile solids and high ash contents because of the high amount of inorganic material (sand), which would make them unsuitable for direct vermicomposting. Sewage sludges had relatively low nitrogen values (<3%) while biosolids had much higher concentrations (5-6% N). Typical nitrogen levels in NZ biosolids are 4% (Sharp, 1992).

Indicator pathogen counts (Table 18) reflected the variation between treatment methods at the wastewater plants. North Shore and Taupo both use

mesophilic digestion and the sludges from these plants had higher counts of indicator organisms. Sludges from the Hamilton plant, which uses a combination of mesophilic and thermophilic digestion, had significantly lower faecal coliforms and *E. coli* populations. Indicator organism concentrations in the four sewage sludges were similar ($10^3 - 10^4$/g).

Table 18: Bulk characteristics of biosolids and sewage sludges (dry weight basis) used in the study.

Source	Moisture (%)	Volatile Solids (%)	Ash (%)	Organic Carbon (%)	Total Nitrogen (%)	Faecal Coliforms (MPN/g)
Anaerobically digested biosolids						
North Shore	82.6	12.4	5.0	41.9	6.2	2.5E+08
Hamilton	73.3	18.0	8.7	43.4	4.8	4.4E+03
Taupo	80.8	13.3	5.9	40.8	5.1	1.3E+07
Stabilisation basin sludges						
Huntly	61.2	4.9	33.9	1.0	0.66	5.7E+04
Ngaruawahia	56.8	4.0	39.2	1.2	0.44	5.3E+04
Te Awamutu	91.7	3.8	4.5	31.1	2.5	2.3E+03
Temple View	93.6	2.0	4.4	20.8	1.9	1.1E+04

The chemical analyses showed that the biosolids had much higher concentrations of the major plant nutrients (P, K, and S) than the sewage sludges (Table 19). Sharp (1992) reported typical values in NZ biosolids of 2% P and 0.2% K. However the biosolids, and particularly those from North Shore and Hamilton, also had higher ammonium-N levels (>0.6%), which could be detrimental to worm health. Sludges from the small community of Te Awamutu had the highest concentrations of the heavy metals, Cu and Zn, which indicates that some activity in the wastewater catchment is adding to more copper and zinc residues than normally expected from corrosion of community plumbing. Sludge from Temple View, the smallest community sampled, had higher Cu and Zn levels than biosolids from the nearby, larger population of Hamilton. Usually sludges from larger communities would have the highest concentrations of Cu and Zn because there is greater potential for contamination from industrial trade

wastes. Wastewater treatment methods as well as locality can affect sludge characteristics as shown by the variations between Waikato District (Huntly and Ngaruawahia) and Waipa District (Te Awamutu and Temple View). Typical values for Cu and Zn found in NZ biosolids are 500 and 1600 mg/kg respectively (Sharp, 1992).

Table 19: Chemical characteristics of biosolids and sewage sludges (dry wt) used in this study.

Biosolids source	Total P (%)	Total K (%)	Total S (%)	NH_4-N (%)	NO_3-N (%	Copper (mg/kg)	Zinc (mg/kg)
Anaerobically digested							
North Shore	1.5	0.16	1.1	**0.74**	0.05	640	850
Hamilton	2.5	0.12	1.0	**0.60**	0.04	420	550
Taupo	1.2	0.07	2.0	0.31	<0.001	460	780
Stabilisation basin							
Huntly	0.2	0.07	0.5	0.03	<0.001	-	200
Ngaruawahia	0.1	0.16	0.7	0.01	<0.001	80	205
Te Awamutu	0.5	0.07	1.1	0.11	<0.001	**920**	**1660**
Temple View	0.5	0.08	0.8	0.11	<0.001	520	830

8.4 Preference studies

- **Study 1**

Worms introduced directly into fresh biosolids exhibited various stress symptoms including yellow secretions, swollen clitellum or blackened colouring followed by death. Most biosolids had more ammonium-N (Table 19) than the 0.05% upper limit that *E. fetida* can tolerate (Edwards, 1988). Edwards (1988) also reported that worms were very sensitive to ammonia and there was a very sharp cut-off around 0.05% between toxic and non-toxic levels.

Worms took 10 days to find biosolids from Taupo acceptable and 14 days for North Shore and Hamilton biosolids. These results reflect the ammonium concentrations. If given no other media, worms took longer to accept the biosolids (18, 21, and 28 days for Taupo, Hamilton, and North Shore biosolids respectively). These results indicated that worms can survive short exposure to

fresh biosolids as long as there is a low ammonia zone to escape to. This would occur in full-scale vermicomposting systems such as raised beds, where biosolids are added to the surface and worms can move freely up and down the profile. The other option is to mix in materials such as lime to alleviate the ammonium.

- **Study 2**

Because the sewage sludges had very high moisture contents, treatments were set up with and without shredded paper. Worms entered the sludges immediately (Table 20), possibly because ammonium levels were lower (Table 19). Adding shredded paper initially increased sludge acceptability but over 30 days, differences between sources and treatments diminished.

Table 20: Effect of sludge and shredded paper on percentage (%) of worms moving from original bedding to the sludge.

Source	Huntly	Ngaruawahia	Te Awamutu	Temple View
Day 1				
Sludge	26	60	73	80
Sludge + paper	53	67	73	93
			SED 21	
Day 2				
Sludge	67	40		
Sludge + paper	67	87		
			SED 22	
Day 5				
Sludge			80	93
Sludge + paper			80	87
			SED 18	

8.5 Vermicomposting biosolids

8.5.1 Changes in properties

Physical

The effect of vermicomposting on stabilising biosolids is best indicated by the reduction in volatile solids (Edwards, 1985). After 30 days the volatile solids of vermicomposted biosolids from North Shore, Hamilton, and Taupo decreased 19, 12, and 13% respectively (Table 21). However, volatile solids of Te Awamutu sludge increased, indicating that it had not been processed enough, probably because its high moisture content (92%) was above the worms' tolerance level of 60-90% (Edwards 1988).

Table 21: Effect of 30 days vermicomposting on physical properties of original biosolids and vermicast produced.

	%	%	Total solids components (%)	
	Moisture	Total solids	Volatile solids	Ash
Biosolids				
North Shore	82.6	17.4	12.4	5.0
Hamilton	73.3	26.7	18.0	8.7
Taupo	80.8	19.2	13.3	5.9
Te Awamutu	91.7	8.3	3.8	4.5
Vermicasts				
North Shore	83.5	16.5	9.4	7.1
Hamilton	77.6	22.4	13.3	9.1
Taupo	83.2	16.8	10.1	6.7
Te Awamutu	86.0	14.0	7.0	7.0

As volatile solids content decreased, there was a corresponding increase in ash (Table 21) and obvious changes in physical appearance (Figure 15).

Chemical

Vermicomposting biosolids reduced carbon and nitrogen levels (Table 22) due to worm respiration and microbial activity. The increase in carbon to nitrogen ratio (Figure 16) demonstrates stabilisation of materials. However, the composition of the sludges did not change appreciably, indicating little processing.

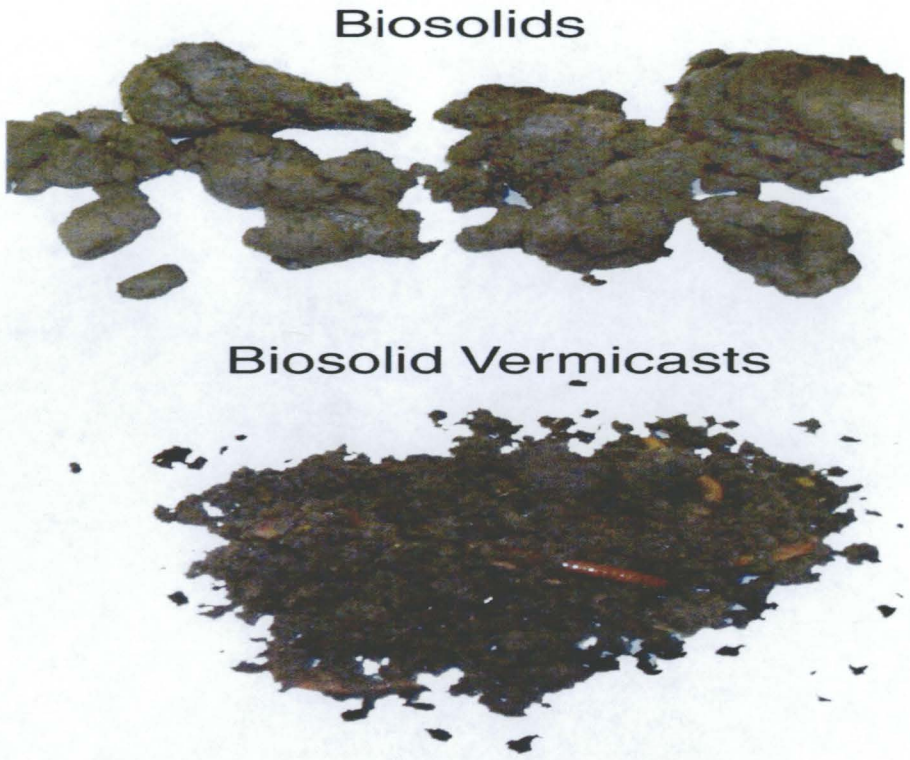

Figure 15: Biosolids before and after vermicomposting.

Table 22: Changes in chemical properties (dry wt) after vermicomposting biosolids.

Source	Carbon (%)	TKN (%)	Total P (%)	Total S (%)	Potassium (%)	NH_4-N (%)	NO_3-N (%)
Biosolids							
North Shore	42.0	6.2	1.5	1.1	0.16	0.74	0.05
Hamilton	43.4	4.8	2.5	1.0	0.12	0.60	0.04
Taupo	40.8	5.1	1.2	2.0	0.07	0.31	<0.001
Te Awamutu	31.1	2.5	0.5	1.1	0.07	0.11	<0.001
Vermicasts							
North Shore	35.8	4.3	1.8	1.4	0.16	0.28	0.07
Hamilton	34.7	3.8	3.0	1.2	0.13	0.57	0.08
Taupo	39.4	3.8	1.5	0.9	0.08	0.14	0.10
Te Awamutu	31.7	2.5	0.5	1.0	0.09	0.06	<0.001

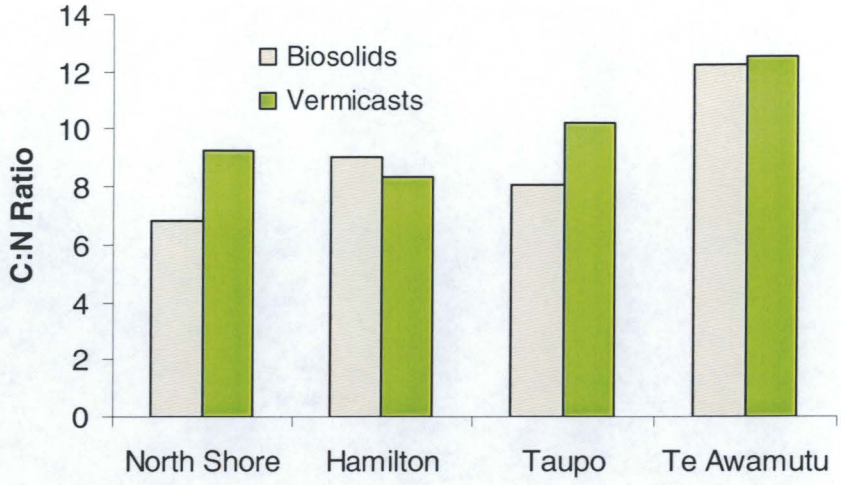

Figure 16: C/N ratio before and after vermicomposting biosolids.

The C/N ratios of these sludges are much lower than the 25:1 optimum suggested by Ndegwa and Thompson (2000). Therefore, longer processing times and/or amendments are needed to achieve stabilisation. Decreases in ammonium-N levels were due to volatilisation losses as the biosolids became more aerobic. Aerobic conditions must occur before worms can tolerate sludges and will be enhanced by worm movement as processing occurs.

Heavy metals

Vermicomposting decreased copper levels in all biosolids but zinc concentrations increased (Table 23. This increase could be due to losses of volatilised carbon and nitrogen, which concentrates elements such as zinc. However, the reason for decreasing copper levels is not known so further investigations are required.

Table 23: Effect of 30-days vermicomposting on copper and zinc levels (mg/kg DW).

	Biosolids		Vermicasts	
Source	Cu	Zn	Cu	Zn
North Shore	640	850	530	950
Hamilton	420	550	320	640
Taupo	460	780	420	870
Te Awamutu	920	1660	1010	1540

The new wastewater industry guidelines (NZWWA, 2003) states the maximum copper and zinc limits for Grade a biosolids (unrestricted use) are 100 and 300 mg/kg DW respectively. Trial results indicate that vermicasts sourced from the wastewater plants in this study would only meet Grade b restricted standards (1250 and 1500 mg/kg for Cu and Zn respectively). Therefore, the effect of diluting biosolids with green or paper wastes needs to be investigated. Vermicomposting to produce material that meets the new standards may be more suitable for smaller communities without the large industrial discharges. However, analyses of wastes from small communities such as Temple View and Te Awamutu have shown (refer Table 19) that even this material may not meet the new standards.

Microbial

One aim of anaerobic digestion is to reduce pathogen levels. However, high total coliforms and *E. coli* can still be found in fresh biosolids (Table 24). Heat in the anaerobic digestion process affects microbial numbers. Coliform populations were lower in biosolids subjected to pasteurisation at higher temperatures such as those from the Hamilton plant that uses thermophilic digesters compared with sludges from Taupo and North Shore that use only mesophilic digestion. The low levels of indicator pathogens in sludge from the Te Awamutu plant are probably due to the dilution effect of microbes spread throughout a water column over a large basin with longer residence times.

Faecal coliforms and *E. coli* indicate faecal pathogens, the higher the count, the greater the chance that pathogenic organisms may be present. Data from this study support other published reports (Lotzof, 1999; Edwards, 1998) and show that even when ideal environmental growth conditions for microorganisms exist, vermicomposting reduces pathogen numbers and especially *E. coli* (Table 24). Vermicomposting appears more effective in reducing pathogens in Hamilton and North Shore biosolids than in material from Taupo. Taupo uses mesophilic treatment, which gives less decomposition. Worms and microbes can degrade more highly digested material faster and with less effort. This was reflected by greater change in characteristics, including microbial, of North Shore and Hamilton biosolids before and after vermicomposting.

Table 24: Effect of 30-day vermicomposting on pathogen reduction (MPN index Log10/g dry wt) of biosolids.

Biosolids	Faecal coliforms		*Escherichia coli*	
Source	Biosolids	Vermicasts	Biosolids	Vermicasts
North Shore	2.5E + 08	9.5E + 02	2.5E + 08	8.0E + 01
Hamilton	4.4E + 03	1.8E + 02	4.4E + 03	3.1E + 01
Taupo	1.3E + 07	5.2E + 05	1.3E + 07	1.3E + 04
Te Awamutu	2.3E + 03	1.7E + 03	2.3E + 03	1.9E + 02

Only vermicasts from North Shore and Hamilton biosolids (Table 24) met the proposed NZ Biosolids Guidelines Grade A for faecal coliforms in stabilised products of <100 MPN/g or <1.0E + 02 (NZWWA 2002). Although vermicomposting was able to reduce pathogens, processing times need to be extended beyond 30 days to obtain products that meet the proposed guidelines.

8.6 Glasshouse trials

8.6.1 Plant yields

Applying vermicasts from any source to cropping soil significantly ($P < 0.001$) increased dry matter yields of ryegrass shoots. As pasture yield responses for 250 and 500 kg N/ha over 30 days were almost identical, the mean

of both rates was used (Figure 17). Plant yields from vermicasts produced from anaerobically digested biosolids were much higher than for vermicasts produced from sewage sludge. These differences were significant from Cut 2 onwards and are mainly due to the lack of soluble N (2% of Total N) in the Te Awamutu material compared with other vermicasts (>6%). Analysis indicated that little nitrogen is available in soluble forms (nitrate-N and ammonium-N) and that most of the Total N is organic-N. Vermicasts from the Hamilton biosolids gave significantly greater plant responses from Cut 4 onwards. This greater response is probably be due to the greater proportion of soluble N (17% of Total N) and higher P content (3.0%), which extends plant growth as the response to the N diminishes. Vermicasts from Taupo sludge outperformed those from the North Shore material from Cut 3 onwards, probably because it has more nitrate-N (0.10% versus 0.07% respectively). While these nitrate-N levels are low, they represent over 40% more N immediately available for plant growth from Taupo vermicasts than from the North Shore material.

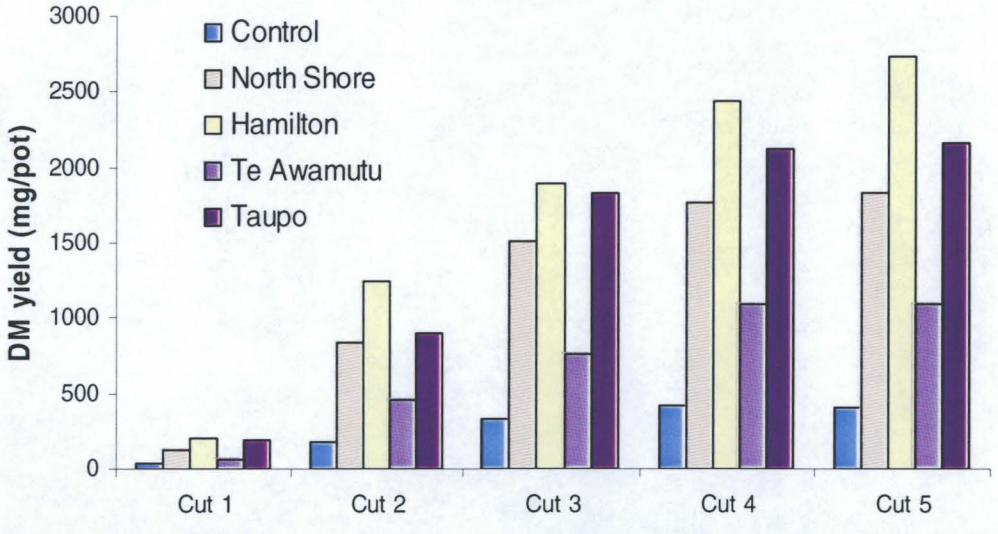

Figure 17: Effect of vermicasts on ryegrass shoot DM yields (mean of both rates). LSD (5%): 180 (between products within time); 310 (between products).

The effect of vermicasts on root biomass is similar to the pattern for shoot yields (Figure 18). Again, due to the small effect of application rate, the overall mean is presented.

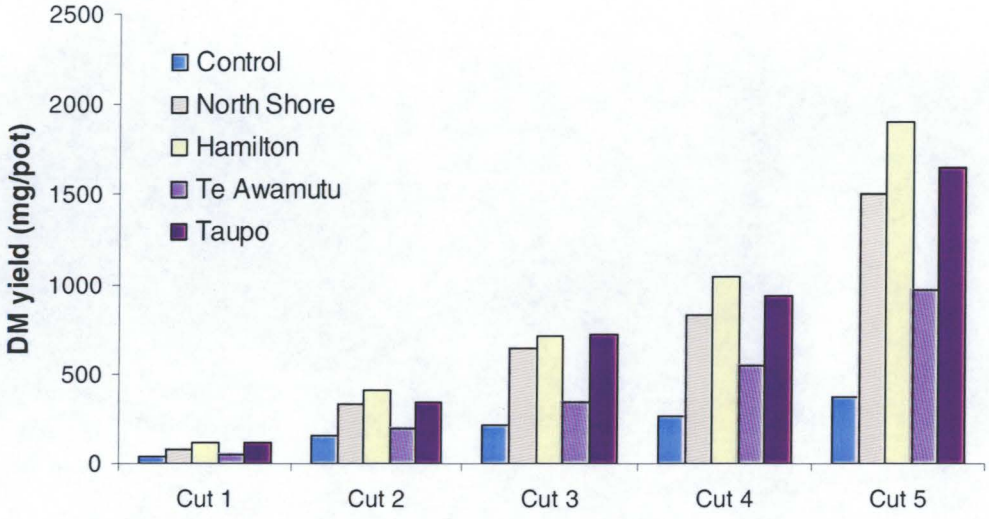

Figure 18: Effect of vermicasts on ryegrass root yields (mean of both application rates). LSD (5%): 160 (between products within time); 370 (between products).

Total biomass (shoot plus root yields) increased over all five samplings and were significantly (*P <0.001*) different, irrespective of application rate or vermicast source (Figure 19). The shoot/root ratio of the Control (no vermicast) treatment was 1.1:1, similar to that reported (Ghani *et al.*, 2003) for ryegrass growth following surface and sub-surface biosolids applications. The mean shoot/root ratio for 250 and 500 kg N/ha rates was 1.2:1 and 1.3:1 respectively, indicating the effect of applying higher soluble N.

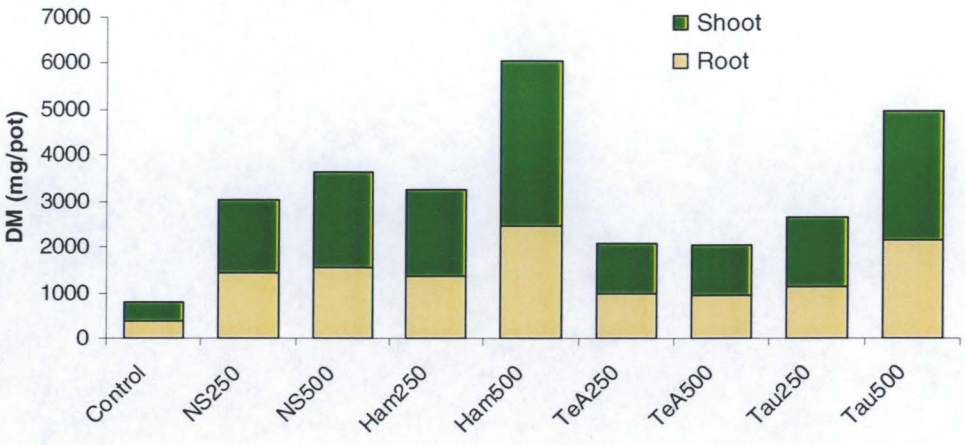

Figure 19: Effect of vermicasts and application rate on total biomass (shoot + roots) yields. LSD (5%): 280 (between products within time); 390 (between products).

8.6.2 Nutrient concentrations and plant uptake

Nitrogen

The MAF standards (1982) for N content (% in DM) of vegetative ryegrass leaf are: deficient (<4.0); low (4.0-4.4); optimum (4.5-5.0); and high (>5.0). Nutrients in Cut 1 were not determined because only a small amount was harvested. However, material from Cuts 2-5 were analysed. Applying vermicasts significantly (*P <0.01*) increased the nitrogen content of the harvested material over that of the Control, but vermicast source had little effect (Figure 20). However, N contents declined with time (Figure 21). Nitrogen in the Control quickly declined from low to deficient status, while leaf from the vermicasts began at optimum to high levels but then decreased to deficient by Cut 5. As plant growth increased with time (Figure 17), the decrease in N content (Figure 21) is probably due to (1) a dilution effect because of extra growth, and (2) exhaustion of the immediately available soluble N reserves.

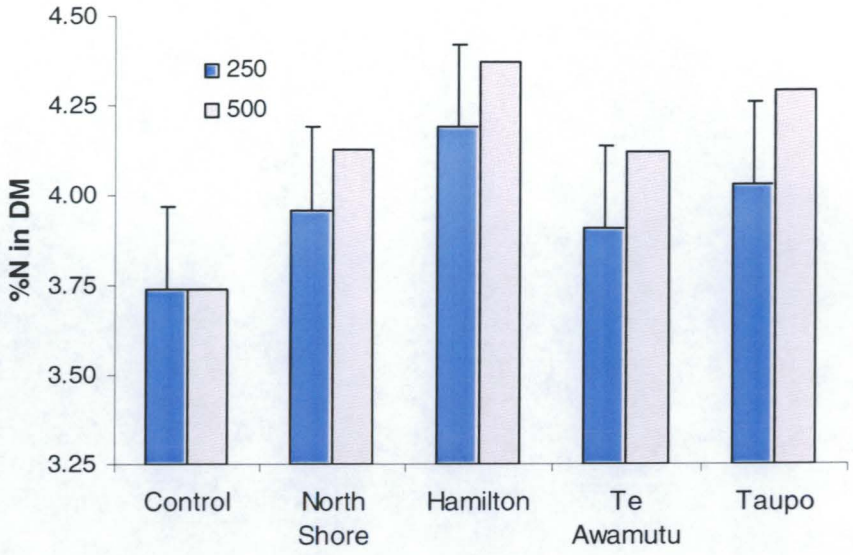

Figure 20: Effect of vermicast source and N application rate on mean nitrogen content in shoot (% of DM) after 90 days growth. LSD (5%): 0.23

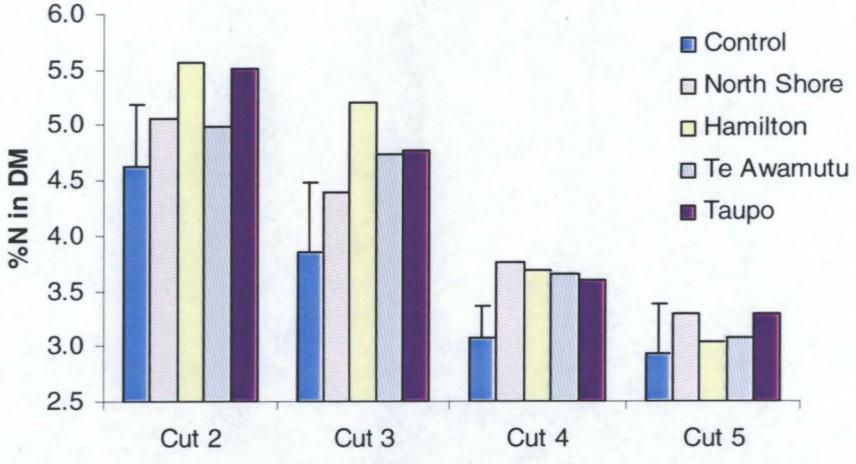

Figure 21: Effect of vermicast source and growing time on nitrogen content (% in DM) in ryegrass shoots.

Nitrogen concentrations of cuts were pooled to calculate mean plant uptake for treatments. The higher N uptake indicated that vermicasts from both Hamilton and Taupo biosolids gave better plant performance (Figure 22). The

high plant yields and N uptake indicate that nitrogen mineralisation was the driving force behind the growth responses.

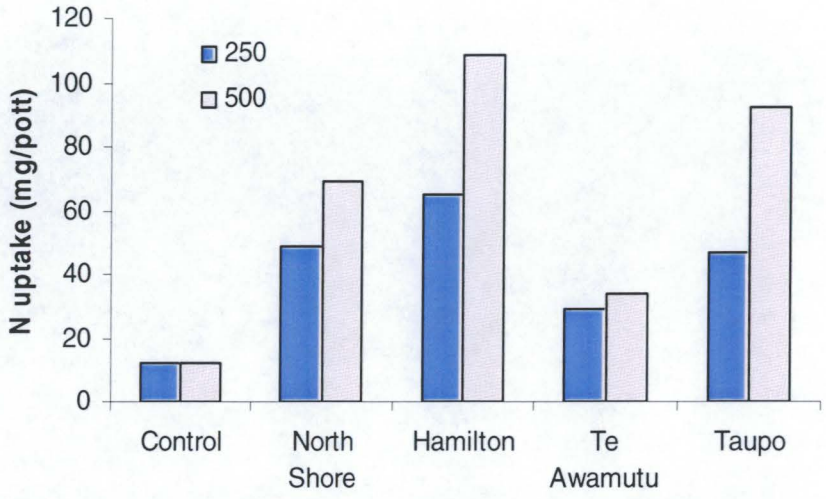

Figure 22: Effect of vermicast source and application rate on nitrogen uptake in ryegrass shoots.

The nitrogen removal efficiency (total N plant uptake to N added) over the 3-month trial was between 5-25% (Figure 23). The N removal efficiency for vermicasts from biosolids was above 15% while removal efficiency for vermicasts from sewage sludge was much lower. This compares with 20% in the first year reported for N mineralisation under field conditions after land application of raw biosolids (Clinton and Leckie, 2002). The higher N mineralisation rates observed in this experiment may be because the soil used had low fertility after prolonged maize cropping, so any additional nitrogen would boost plant growth. .

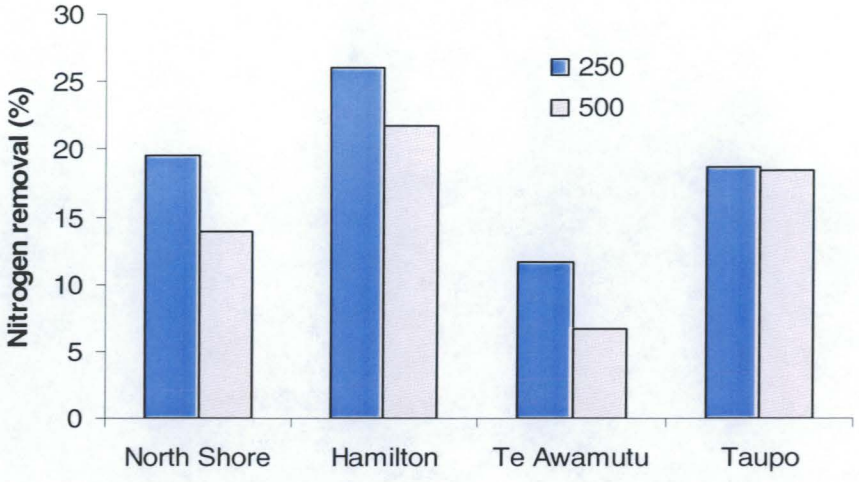

Figure 23: Effect of vermicasts and application rate on nitrogen removal after 3 months.

Phosphorus

The MAF standards (1982) for P content (% in DM) of vegetative ryegrass leaf are: deficient (<0.30); low (0.30-0.35); optimum 0.35-0.40); and high (0.40-0.45). Phosphorus concentrations in shoots decreased with time but the vermicasts source affected this decrease (Figure 24). Leaf from Hamilton biosolids had very high concentrations (>0.45%) at Cut 2 and then decreased steadily. Leaf grown on vermicasts from North Shore and Taupo biosolids had high concentrations (>0.40-0.45%) for Cuts 2 and 3, and then decreased slowly to 0.35-0.40% for Cuts 4 and 5. Growth on vermicasts from Te Awamutu sludge was poor and can be partly attributed to its deficient P concentration (<0.30%), which was below the low levels (0.30-0.35%) in the Control and is shown more clearly in the pooled data (Figure 25).

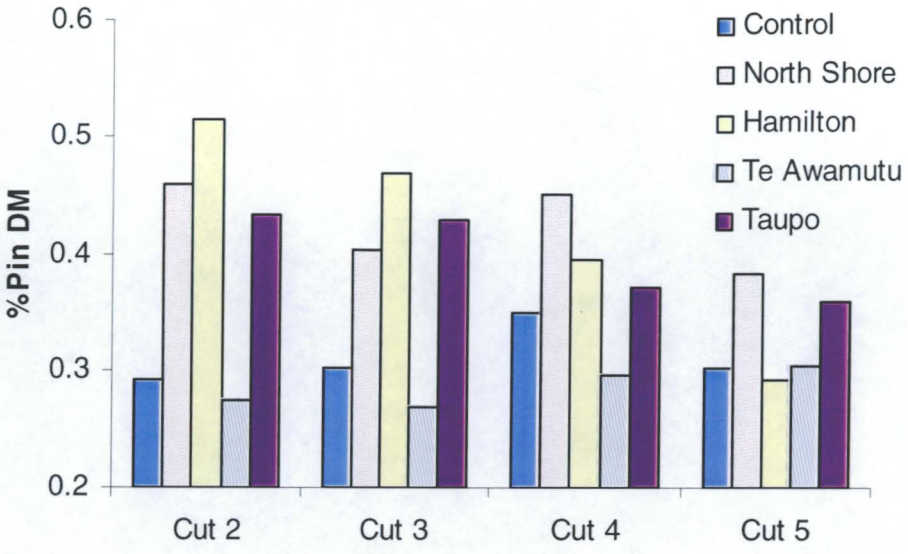

Figure 24: Effect of vermicast source on phosphorus concentrations (% in DM) in ryegrass shoots over time.

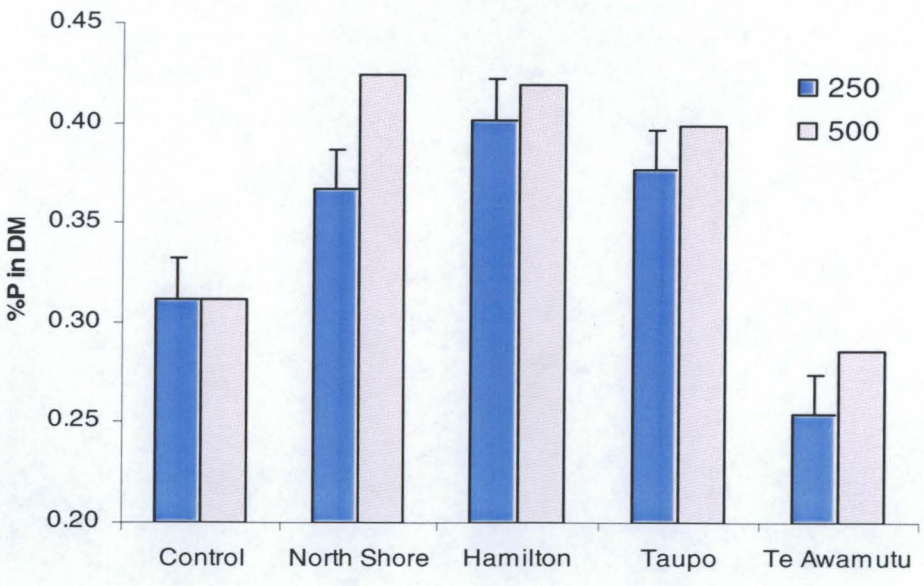

Figure 25: Effect of vermicast source on pooled mean P concentrations (% in DM) in ryegrass shoots. LSD (5%): 0.02.

8.6.3 Heavy metals

Ryegrass shoots grown on vermicasts from Te Awamutu sewage sludge had significantly higher (*P <0.001*) zinc concentrations than those grown on vermicasts from biosolids (Figure 26) and reflect the initial concentrations in the applied vermicasts (Table 23). The lowest zinc concentrations occurred in shoots grown on vermicasts from Hamilton biosolids, which approached the levels in the Control by Cut 4 (Figure 27).

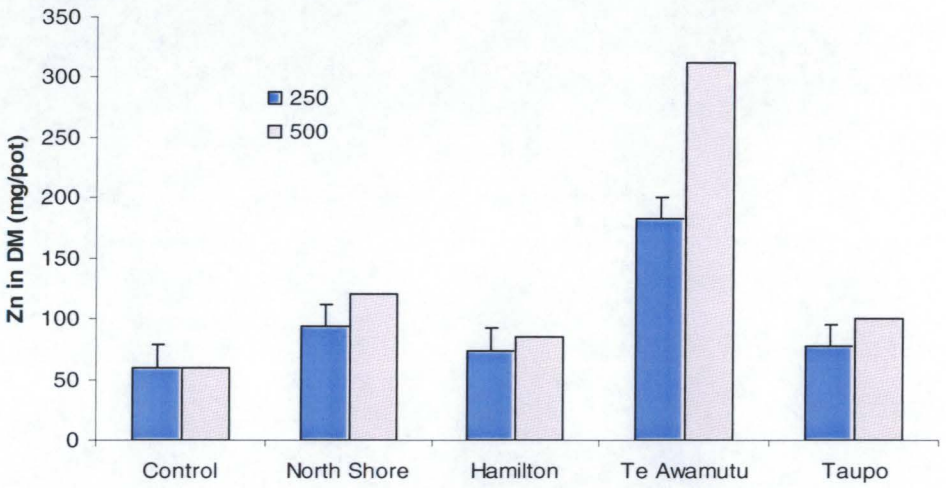

Figure 26: Effect of vermicast source and application rate on pooled mean zinc concentrations (mg/kg DM) in ryegrass shoots.

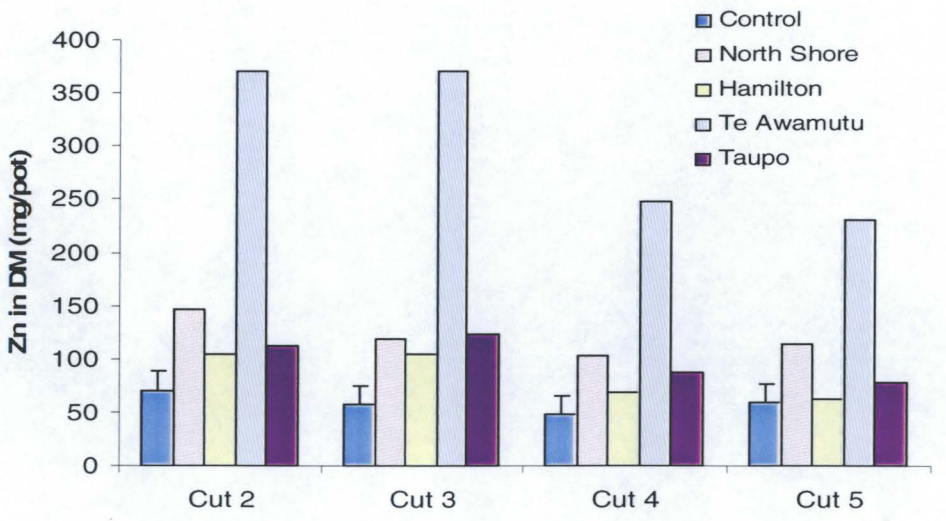

Figure 27: Effect of vermicast source on zinc concentrations (% in DM) in ryegrass shoots.

Ryegrass grown on vermicasts from Te Awamutu sludge had much higher zinc contents than ryegrass grown on other media. Zinc may not be bound to organic matter in the Te Awamutu vermicasts and therefore likely to be taken up by the ryegrass. This is supported by the very low N mineralisation from this media (Figure 23). Digestion rate in a stabilisation pond can take several months because it relies on anaerobic microbe decomposition, whereas decomposition in biosolids (e.g., Hamilton material) is quicker because of the thermophilic/mesophilic digestion (26-28 days). Thus, zinc is bound to organic matter and less is released to plants.

Ryegrass growth is optimum when zinc concentrations are 14-20 mg/kg DM (MAF, 1982). About 25 mg/kg is needed to maintain animal health but zinc can become toxic to livestock at 900 mg/kg (Ellison and Feyter, 1988). Plant zinc concentrations in ryegrass shoots grown on vermicasts from biosolids are within the interquartile (25-75% range) of values for pastoral grasses (Longhurst *et al.*, 2004). Zinc is readily absorbed by plant roots and translocated to shoots. However, plants would suffer severe yield reductions from excessive zinc concentrations before humans or livestock are put at risk from consumption of affected crops, thus phototoxicity protects the food chain (Chaney, 1980).

The new Biosolids Guidelines (NZWWA, 2003) reduce maximum zinc concentrations in biosolids from 600 mg/kg (until 12/12/2012) to 300 mg/kg (after 12/12/2012). The new limits will prevent the chance of Zn, which is relatively mobile in soils, from leaching to groundwater. However, this new limit would also prevent vermicomposted biosolids being used in soil applications (Table 23). Thus, there is the dilemma of implementing the MfE waste strategy of beneficial reuse (Wigley, 2002) yet having to meet the more stringent application guidelines of the wastewater industry (NZWWA, 2003). High zinc (and copper) concentrations are often due to domestic inputs and cannot be controlled by trade waste bylaws. Adjusting water pH can reduce pipe corrosion and has the potential to reduce copper and zinc inputs (NZWWA, 2003).

8.6.3 Pathogens

Faecal coliform and *E. coli* concentrations were very low (Table 25) and often below the MPN detection limit in soil of <1.8/g (Upali Sarathchandra, AgResearch, pers. comm.). They were similar to levels in pastoral soils (Andrea Donnison, AgResearch, pers. comm.). Because of the low concentrations found, statistical analysis was not possible.

Table 25: Effect of vermicompost source on faecal coliforms and *E. coli* (MPN per g dry soil) during ryegrass growth.

	Cut 1	Cut 2	Cut 3	Cut 4	Cut 5
Faecal coliforms					
Control	1.9	5.9	3.5	5.7	6.3
North Shore	0.7	2.6	2.2	5.3	3.2
Hamilton	0.2	<1.8	2.3	4.6	4.7
Te Awamutu	8.1	4.7	2.2	4.2	5.0
Taupo	3.0	2.2	4.7	9.3	6.6
Escherichia coli					
Control	1.6	5.9	2.2	2.5	2.2
North Shore	0.7	2.6	<1.8	<1.8	<1.8
Hamilton	0.2	<1.8	<1.8	2.5	1.9
Te Awamutu	8.1	3.3	<1.8	1.9	2.6
Taupo	2.7	2.2	<1.8	4.5	<1.8

A threshold of >200 faecal coliforms per 100 ml for recreational water is considered to constitute a health hazard from pathogenic enteric bacteria. If the soil-vermicast mix is assumed to have a bulk density of 650 kg/m^3, then 200 bacteria in 100 ml (65 g) of mix represents three bacteria per g of soil. The highest count (17 faecal coliforms per g) occurred in a Hamilton sample from the fourth cut. Although this is nearly six times greater than the limits for water, it is still an extremely low concentration for soil and is unlikely to be a heath hazard for humans working on the land or animals grazing pastures where vermicasts have been applied (Andrea Donnison, AgResearch, pers. comm.).

Total coliforms were greater than faecal coliforms or *E. coli* populations. Total coliforms in the Control soil were relatively constant during the experiment. Vermicast source significantly ($P < 0.01$) affected total coliform counts at Cut 2 (Table 26). The high value in Hamilton vermicasts at Cut 4 may be due to over-watering the pots on a long weekend before harvest, which saturated the soil. By Cut 5, total coliforms in Hamilton vermicast material were similar to those in the other soils.

Table 26: Effect of vermicast source and time on total coliforms (Log10/g soil).

Vermicast source	Harvests after vermicast application			
	Cut 2	Cut 3	Cut 4	Cut 5
Control	1.62	1.87	1.56	1.47
North Shore	**2.52**	2.43	2.02	**2.21**
Hamilton	**2.66**	2.28	**3.11**	1.95
Te Awamutu	**2.95**	2.38	1.83	**2.16**
Taupo	2.11	1.97	2.10	1.79
LSD (5%)	0.66	0.66	0.66	0.66
Significance	**	ns	**	**

Data for total coliform concentrations (averaged across sampling times) showed that vermicast/soil mixes had higher concentrations than Control soils (Figure 28). Total coliforms declined steadily with time to 53, 84, 83, and 47% of the original populations for North Shore, Hamilton, Te Awamutu and Taupo materials respectively.

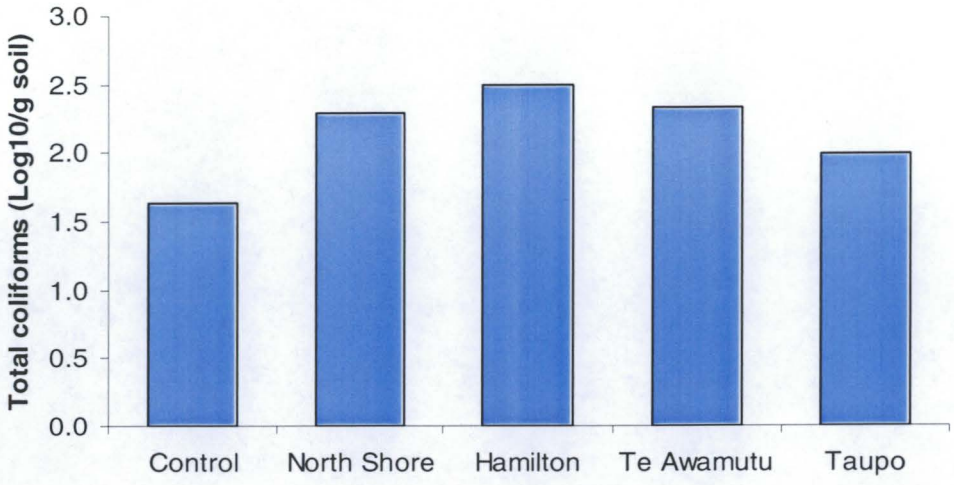

Figure 28: Effect of vermicast source on total coliform counts (MPN $\log_{10}$) in vermicast/soil mixes (mean of biosolid sources). LSD (5%): 0.33.

Chapter 9 Summary

Four aspects of vermicomposting were investigated. The following is a summary of the findings:

9.1 Characterisation of the biosolids and sewage sludges

Biosolids and sewage sludges from seven different municipal waste treatment plants were characterised. The waste treatment process influenced the characteristics of the biosolids. Dewatered anaerobically digested biosolids from large wastewater treatment plants (servicing 30,000-180,000 people) had higher organic matter, N and P levels and lower heavy metal contents than sewage sludges from waste stabilisation basins of smaller communities (800-8,000 people). Zinc concentrations in Te Awamutu sludge (1660 mg/kg DM) were over twice those of any other community. Indicator pathogens (measured as *E. coli*) were higher in fresh biosolids (10^3 - 10^8g) than raw sewage sludge (10^3 - 10^4g). The method of sludge digestion influenced the degree of pathogen reduction. Thermophilic/mesophilic digestion gave superior pathogen reduction (10^3) compared to mesophilic only digestion (10^7 - 10^8g).

9.2 Worm acceptance of materials

Anaerobically digested biosolids were toxic to worms, primarily because of its higher initial ammonia levels (>0.5%). However, worms could survive on these materials if alternative bedding was available. Earthworms accepted all the biosolids offered after 10-14 day withholding periods. Sewage sludges had higher moisture contents (57-94%) than biosolids (73-83%) but were accepted after only two days. Adding shredded paper and cardboard to sewage sludges absorbed excess moisture and increased its acceptability.

9.3 Effect of vermicomposting biosolids and sewage sludges

After vermicomposting these materials for 30 days, their physical, chemical and microbiological properties changed. Biosolids were stabilised more

than sludges with higher moisture contents. However, none of the vermicasts achieved the optimal C/N ratio of 20-25:1, indicating more processing time was required. Total N and ammonium-N concentrations in all materials decreased after vermicomposting while phosphorus and nitrate-N levels increased. Vermicomposting decreased copper concentrations in biosolids but not in sludges. Zinc concentrations showed the reverse trend. Copper and zinc concentrations in vermicasts were all above the maximum Grade a contaminant levels of 100 and 300 mg/kg respectively in the new biosolid guidelines (NZWWA, 2003). Vermicomposting significantly decreased pathogen numbers from 10^4-10^9 to 10^2-10^4 MPN/g.

9.4 Agronomic evaluation of vermicasts

Ryegrass biomass (shoot and root growth) over 90 days (5 cuts) in glasshouse trials was significantly higher on vermicast/soil mixes than on Control soil. Vermicast produced from Hamilton biosolids had the highest soluble N (0.65%) and P (3.0%) content and gave the highest growth response. Plant growth on vermicasts from Te Awamutu sludge was poor and linked to the very low soluble N (0.06%) and P (0.5%) levels. Heavy metal concentrations (using zinc as the indicator) were highest in shoots grown in vermicasts from Te Awamutu sludge (mean 240 mg/kg) and reflected concentrations from their sewage sludge. Plant zinc concentrations grown in vermicasts from biosolids were similar to Control levels by the fifth cut. Although indicator pathogen counts (total coliforms) in all vermicasts were higher than Control (50 per g), the populations were lower than those normally found in pastoral soils.

Vermicomposting is an effective method for stabilising biosolids. The vermicasts produced can supply soils with valuable humus and nutrients, which ensures beneficial reuse of a product that is usually considered 'waste'.

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Vermicomposting of biosolids for beneficial reuse

agresearch

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Introduction

- Vermicomposting, a process where earthworms and microbes break down organic wastes.
- Worms require highly moist (80-85%) and aerobic conditions.
- Natural and ecologically friendly method of waste stabilisation.

Aim

To investigate the effectiveness of vermicomposting in improving the physical, chemical and biological attributes of biosolids from different wastewater processing plants.

Materials & Methods

Biosolids characteristics

Some physical and chemical characteristics of fresh AD biosolids and SB sludges (dry weight basis)

	Source/treatment	Total solids (%)	Carbon (% DM)	NH_4-N (% DM)
Biosolids anaerobically digested (AD) - mesophillic (35ºC) - thermophillic (55ºC)	North Shore (meso)	17.1	41.9	0.74
	Hamilton (thermo)	25.9	43.4	0.60
	Taupo (meso)	19.8	40.8	0.31
Sewage sludge stabilisation basin (SB)	Te Awamutu	8.2	31.1	0.11
	Temple View	8.4	20.8	0.11
	Huntly*	38.8	1.0	0.03
	Ngaruawahia*	43.2	1.2	0.01

Two SB sludges not suitable for vermicomposting as organic matter content too low.

Investigations

- Worm preference studies
- Physical, chemical, biological measurements before and after vermicomposting for 30 days

Results & Discussion

Preference studies

- Fresh anaerobic biosolids toxic to worms – ammonium-N levels too high ?
- How long before NH_4-N decreases to tolerable levels?

Time taken for worms to find biosolids acceptable

Biosolid source	Days
North Shore	14
Hamilton	14
Taupo	10
Te Awamutu	2
Temple View	2
Huntly	3-5
Ngaruawahia	3-5

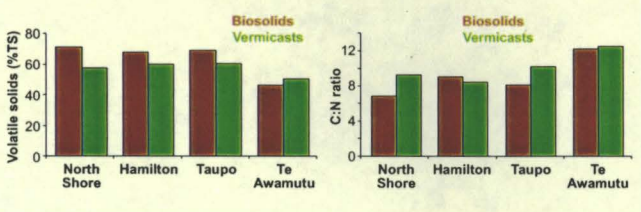
Addition of shredded paper encouraged worms into SB biosolids which were too wet otherwise

Impact of vermicomposting on:

Stabilisation

Volatile solids (VS) used as indicator of stabilisation.

Worms effective in reducing VS in AD biosolids, however Te Awamutu SB sludge was too wet.



Ammonium and heavy metals

dry weight basis

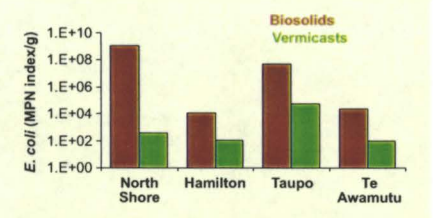
C/N ratio increased, NH_4-N decreased, heavy metals variable results.

Biosolids source	Total carbon (%)		Total nitrogen (%)		NH_4-N %		Cu mg/kg		Zn mg/kg	
	Biosolids	Vermicasts	Biosolids	Vermicasts	Biosolids	Vermicasts	Biosolids	Vermicasts	Biosolids	Vermicasts
North Shore	43.4	35.8	4.8	4.3	0.74	0.28	640	530	850	945
Hamilton	42.0	34.7	6.2	3.8	0.60	0.57	420	320	550	640
Taupo	40.8	39.3	5.1	3.8	0.31	0.14	460	420	780	870
Te Awamutu	31.1	31.7	2.5	2.5	0.11	0.06	920	1010	1660	1540

Pathogens

MPN index/g - dry weight basis

Initially high populations in mesophillically treated biosolids. Significant pathogen reductions achieved by worms.



Conclusions

- Worms found all anaerobically digested biosolids acceptable within 14 days.
- Stabilisation basin sludges more acceptable for vermicomposting.
- Volatile solids reductions of 17-22% achieved after 30 days.
- Variable results on nutrient and heavy metal concentrations.
- Significant reductions in pathogen numbers.
- Vermicomposting appears to be a viable option for biosolid stablisation.

Courtesy of Vermitech Ltd, Australia

Agronomic performance of vermicomposted biosolids

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Introduction

- New Zealand produces 400,000 tonnes of wet biosolids/sewage sludge annually.
- Over $8-10 million of plant nutrients is locked into biosolids/sewage sludge.
- Nutrient contents in biosolids/sewage sludge may vary depending on inputs, sludge processing and stabilisation methods at wastewater treatment sites.
- Beneficial re-use of biosolids/sewage sludge on land will depend on the agronomic effectiveness, pathogen risk and heavy metal risks.

Aims

To investigate agronomic effectiveness of four vermicomposted biosolids.

To assess nutrient uptake, pathogen persistence, and heavy metal fate.

Materials & Methods


Biosolid vermicasts

Some physical, chemical and biological characteristics of vermicomposted biosolids (dry weight basis)

		Moisture (%)	N* (%)	P* (%)	Soluble N* (%)	Zn* (ppm)	Faecal coliform (MPN/g biosolid)
Biosolids: anaerobically digested	North Shore	84	4.3	1.8	0.35	950	9.5×10^2
	Hamilton	78	3.8	3.0	0.65	640	1.8×10^2
	Taupo	83	3.8	1.5	0.23	870	5.2×10^5
Sewage sludge: stabilisation basin	Te Awamutu	86	2.5	0.5	0.06	1540	1.7×10^3

* total contents

Soil: continuously cropped volcanic ash: pH 6.7; Total N 0.5%; Olsen P 23

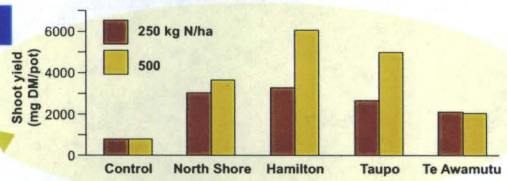
Experimental design: 4 materials x 2 addition rates (250 and 500 kg N/ha), plus control x 3 replicates x 5 destructive samplings over 90 days

Measurements:
Shoot and root dry matter yields
Nutrients: nitrogen (N) and phosphorus (P)
Pathogens: total coliforms (as indicator organism)
Heavy metal: zinc (Zn)

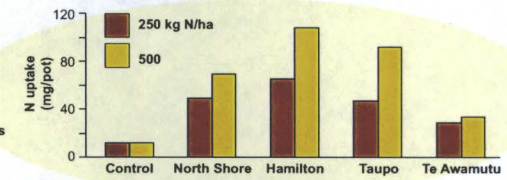
Results

Agronomic response

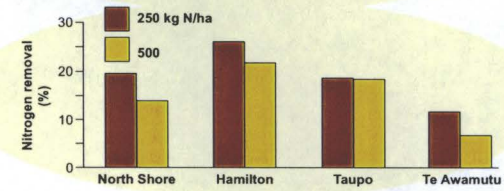
Ryegrass shoot DM yields (mg/pot) over five cuts



Total N uptake (mg/pot) in ryegrass shoots



Total N removed (%) in ryegrass shoots

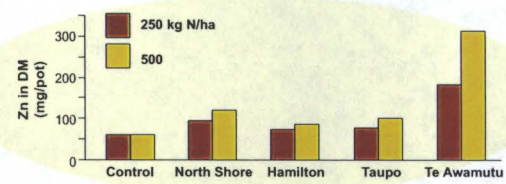


Pathogen persistence

Total coliforms (MPN) in soils treated with vermicomposted biosolids

Heavy metal fate

Zinc concentrations (mg/pot) in ryegrass shoots



Conclusions

- Plant yields were significantly *(P <0.001)* increased by vermicomposted biosolids
- Soluble component of total N was main driver of agronomic responses
- Agronomic performance was better from two-stage (thermophilic/mesophilic) anaerobically digested biosolids e.g. Hamilton
- Total coliform concentrations were lower than that found in most pastoral soils
- Zinc concentrations can be higher from smaller communities e.g. Te Awamutu sludge
- Proportion of soluble N in the biosolids affects relative agronomic yields.
- N removal varied between 7-25%.
- Low pathogen risks.
- Zn uptake dependent on initial concentration.