Evaluation of the Processing Capacity of On-Site In-Vessel Vermiculture Technology

Final Report

Recycled Organics Unit

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Resource NSW

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The Recycled Organics Unit (ROU) is a joint project between Resource NSW and The University of New South Wales to provide a NSW centre for organic resource recovery, management, research and development, demonstration and training.

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Section 1: Executive summary

1.1 Introduction and summary of key objectives

This study aimed to determine the maximum processing capacity for processing of common compostable organic materials produced by the commercial and industrial (C&I) sector by on-site, continuous flow vermiculture technology. Typical materials produced by target C&I markets include fruits and vegetables from supermarkets; mixed food organics from retirement villages, schools, hotels and government institutions; and cardboard packaging common across the sector.

This trial builds upon the outcomes of a previous bench-scale trial (Recycled Organics Unit, 2000) that examined the potential for processing monostreams of food organics using vermiculture technology. The processing capacities investigated in this trial were based on the materials and loading rates proposed by the bench-scale trial. The current trial, however, evaluated these processing capacities on a larger scale in vermiculture units that reflect those available to C&I sector enterprises.

The objective of this vermiculture trial was to confirm the applicability of maximum processing capacity data produced in the bench-scale trial. The two relevant food organics combinations that were identified to have the greatest processing capacity were: fruit and vegetables and mixed food organics (Recycled Organics Unit, 2000). The processing capacities for these materials were evaluated after amendment with a cardboard bulking agent to form a suitable feedstock mixture. The on-site system monitoring procedures suggested by this trial were also evaluated as a means of indicating the health of a vermiculture unit.

With such information, vermiculture technologies can be implemented into appropriate circumstances in the C&I sector with confidence, thereby reducing the amount of compostable organics materials disposed of in landfill.

1.2 Summary of key findings

The vermiculture trial was performed over 6 months and was divided into two stages: a preliminary stage (weeks 1 to 12) and a final stage (weeks 13 to 24). This report details the findings from entire trial performed over 24 weeks.

The trial was performed using six vertical loading, continuous flow vermiculture units located in a temperature controlled laboratory. Mature vermicast was loaded into the vermiculture units to a depth of 0.3 m and the units were inoculated with Tiger worms (*Eisenia* spp.) at a rate of 18.5 kg m^{-2} of bedding surface area.

The two feedstock mixtures examined in the trial were representative of organic materials common to C&I sector waste streams. These feedstocks were: (1) a fruit/vegetable/cardboard feedstock consisting of a variety of mixed fruit and vegetables and shredded cardboard; and (2) a mixed food organics/cardboard feedstock, consisting of mixed fruit and vegetables, bread, meat/poultry and shredded cardboard. Each treatment was replicated three times. Particular attention was paid to the preparation of the feedstocks prior to processing in the vermiculture units. This preparation involved size reduction of all components and amendment of food materials with a sufficient quantity of cardboard bulking agent to achieve a suitable carbon to nitrogen (C:N) ratio and moisture content for vermiculture processing.

Chemical and physical analysis of the amended feedstocks was performed for comparison against the quality of the vermicast product at the completion of the final stage of the trial. The chemical and physical analysis of the feedstocks included moisture content, pH and electrical conductivity. These characteristics were all found to be within the optimal range. The feedstock was also analysed for the presence of heavy metals and microbial pathogens.

The loading rates of feedstocks for this trial were based on recommendations from the bench-scale vermiculture trial (Recycled Organics Unit, 2000). The initial loading rate for the amended fruit/vegetable/cardboard feedstock was 20.6 kg m^{-2} wk^{-1} (30 L m^{-2} wk^{-1}) and the initial loading rate for the mixed food organics/cardboard feedstock was 7.8 kg m^{-2} wk^{-1} (15 L m^{-2} wk^{-1}).

Comprehensive monitoring of the vermiculture units was performed throughout the trial. Monitoring of chemical and environmental characteristics was performed to ensure the feedstocks were processed effectively and that the vermiculture units were operating efficiently. The monitoring regime was based on a hierarchy of system performance indicators established by the bench-scale vermiculture trial. This hierarchy of performance indicators was evaluated in the current trial and included: worm activity, accumulation of unprocessed feedstock and chemical/environmental monitoring data (temperature, oxygen concentration, pH and EC).

The feedstocks used in this study were found to be readily treatable using vermiculture technology. However, after a number of weeks, the system performance indicators suggested that vermiculture units receiving fruit/vegetable/cardboard feedstock were not operating at an optimal level. The worm population had migrated to the edges of the feedstock layer, there was an accumulation of unprocessed feedstock, temperatures had reached the critical level (30 ^{o}C) and oxygen concentrations were also critical (5%). The loading rate was consequently reduced by 20% to 16.5 kg m^{-2} wk^{-1} (24 L m^{-2} wk^{-1}) as shown in Table 1.1.

Conversely, the mixed food organics/cardboard feedstock was performing at an optimal level and hence the feedstock loading rate was increased by 20% to ensure the maximum processing capacity was reached. The final loading rate at the completion of the preliminary period was 9.4 kg m^{-2} wk^{-1} or 18 L m^{-2} wk^{-1} as shown in Table 1.1.

Table 1.1. Initial and final processing loading rates for the two feedstocks examined in this trial.

Feedstock		Loading rate (per application)[1,2]		Loading rate (per week)[1]	
		L m^{-2}	**kg per unit**	**L m^{-2} wk^{-1}**	**kg m^{-2} wk^{-1}**
Fruit/vegetable/ cardboard	Initial loading rate Week 1-10	10	3.65	30	20.6
	Final loading rate Week 11-24	8	2.92	24	16.5
Mixed food organics/ cardboard	Initial loading rate Week 1-4	5	1.38	15	7.8
	Final loading rate Week 5-24	6	1.66	18	9.4

[1] Note that the loading rate included a cardboard bulking agent and additional moisture where appropriate (see Table 2.1).
[2] Application of feedstock occurred three times per week from week 3. The initial loading rates were altered and the final loading rates were found to be more successful at the completion of the trial.

The hierarchy of system indicators determined in the bench-scale vermiculture trial (Recycled Organics Unit, 2000) and used in this trial, allowed a detailed evaluation of the health and performance of the vermiculture units. At the completion of the preliminary period, the system performance hierarchy indicated the potential failure of the fruit/vegetable/cardboard feedstock and the required loading rate increase for the mixed food organics/cardboard feedstock to ensure maximum processing capacity was reached.

At the completion of the preliminary period, the temperatures within the vermiculture units for both feedstocks were not stable indicating that the units had not reached approximate steady-state conditions. An extension of the trial by a further 12 weeks was required to determine if the revised loading rates were more suitable.

The worm population successfully processed the revised loading rates for both the fruit/vegetable/cardboard feedstock and the mixed food organics/cardboard feedstock. The performance indicators showed that the units were operating successfully and that approximate steady state conditions had been reached after 24 weeks. This was indicated by the low variation in oxygen concentrations and temperatures within the units and the observations of worm activity and feedstock accumulation according to optimal criteria.

1.3 Recommendations

1.3.1 Skills based training

The outcomes of the vermiculture research program to date should be developed into a skills based training program: "How to install and manage a successful on-site vermiculture organics management system". This program should be delivered to selected Resource NSW, NSW EPA and Local Government staff thereby enabling key staff to deliver the training program throughout New South Wales.

1.3.2 On-site commercial vermiculture trial

The establishment of an operational on-site vermiculture installation for a C&I sector organisation would provide validation of the results in a real world situation with reduced control over environmental conditions. This project will provide valuable data and case study experience regarding establishment, operation and viability of such an organics management system. A trial of this nature would provide cost/benefit financial data that could assist in decision making. Such cost/benefit data does not currently exist for use of on-site vermiculture technology in the C&I sector.

1.3.3 Acclimatisation

The amount of time required for worm stock to adjust to a feedstock has been found to be a critical issue in setting up and managing a successful on-site vermiculture unit. In this trial, and others, it had been found that changes in feedstock composition (eg. manure to food organics) can result in a delay in processing as the worm population adjusts or acclimatises to the new feedstock. The same situation occurs with changes in the feedstock loading rate. An acclimatisation study would provide information on the process of increasing loading rates in a sustainable manner.

1.3.4 Minimum recommended duration for related vermiculture trials

As a result of this trial, and others, it is recommended that the minimum duration for related vermiculture trials be not less than 6 months. This duration is considered necessary to develop steady state conditions and therefore to deliver meaningful results.

Section 2: Mid-scale vermiculture trial

2.1 Introduction

Processing of agricultural organic materials such as manures, biosolids and crop residues using vermiculture technology has been well documented, however, the potential for vermiculture to process organics produced by the commercial and industrial (C&I) sector has received little attention (Recycled Organics Unit, 2000). Vermiculture technology offers a viable means of recycling organics on-site with the opportunity of producing a valuable end product of vermicast.

Previous studies have examined the capability of vermiculture technology to process mixed vegetables, mixed fruit, manure and garden organics (Edwards, 1995, 1998; Frederickson *et al.*, 1997; Gosh *et al.*, 1999; Vermitech, 2000), however there has been little work done on the processing capacity of highly putrescible compostable organics such as mixed food organics containing meat, poultry and breads (Recycled Organics Unit, 2000).

This trial was performed to evaluate and assess the processing capacity of vermiculture units for typical organics streams produced by C&I sector enterprises. This trial follows on from a bench-scale vermiculture trial that assessed the capacity of small-scale units to process monostreams of organics (Recycled Organics Unit, 2000). Examples of such monostreams include breads and pastries from bakeries; vegetables and fruit from supermarkets; and meat and poultry from specialist retail outlets and food processing operations.

The bench-scale vermiculture trial found that particular monostreams of food organics such as meat/poultry and breads cannot be processed in vermiculture units and that a bulking agent, such as cardboard, is required for efficient processing of fruits and vegetables. These results will be confirmed on a larger scale in this trial so that the maximum processing capacities of on-site vermiculture technologies can be determined and the on-site management requirements can be confirmed.

Mid-scale refers to a category of on-site organics recycling. On-site mid-scale is defined as a category of on-site vermiculture-based technology with the ability to process between 20 and 250 kg of compostable organics per day. Such systems are usually comprised of an in-vessel processing unit and size reduction equipment, for example a garden type petrol driven chipper or shredder. Mid-scale systems are often used for the treatment of compostable organics produced by the commercial and industrial sector such as hospitals and institutions (Recycled Organics Unit, 2001a).

This trial aimed to represent the processing of organic materials, produced by the C&I sector, by on-site, continuous flow vermiculture units. The organic materials included some materials that are typically produced by target C&I sectors. These producers include supermarkets that produce organic materials comprising mixed fruits and vegetables, and retirement villages, schools, hotels, or government institutions with typical organic materials of mixed food organics comprising fruit and vegetables, bread, meats and poultry. Mixed fruit and vegetables and mixed food organics were found to be the most treatable C&I sector organics in the bench-scale trial (Recycled Organics Unit, 2000).

The current trial was performed over 24 weeks and divided into two stages, the preliminary stage and the final stage. The preliminary stage spanned the first 12 weeks of the trial and the final stage spanned the final 12 weeks of the trial. This final report details the results obtained from the entire trial and confirms the maximum processing capacities of these two streams of organic materials for continuous flow vermiculture units as recommended by the bench-scale vermiculture trial (Recycled Organics Unit, 2000) and the Preliminary Report (Recycled Organics Unit, 2001b).

This trial provided the basis for the development of best practice guidelines for the set-up, installation and management of on-site vermiculture technology for processing of C&I sector compostable organics (Recycled Organics Unit, 2002).

2.2 Materials, methods and experimental design

2.2.1 Pre-processing of feedstock

Two compostable organics streams were utilised in this study to determine the viability of processing organic materials by on-site in-vessel vermiculture units. The organic materials used in this trial included mixed fruit and vegetables, and mixed food organics. These materials were selected to represent organic materials typically produced from target markets where on-site vermiculture technology may be suitable. The typical market for mixed fruit and vegetable organics include supermarkets whilst the typical markets for mixed food organics include retirement villages, schools, boarding schools, large hotels and government institutions.

The organic materials were sourced from a number of businesses around Sydney and were blended with a cardboard bulking agent to result in a suitable feedstock for vermiculture processing. The fruit and vegetable feedstock, prior to the addition of a cardboard bulking agent, was comprised of 50% fruit and 50% vegetables by volume. The mixed food organics feedstock, prior to the addition of a cardboard bulking agent, was comprised of a blend of 30% fruit, 30% vegetables, 20% bread and 20% meat/poultry by volume. The major components of each feedstock were identified, however, actual proportions of each were not quantified. Details of the two feedstocks, including the major components of each, are shown in Table 2.1.

Table 2.1. List of feedstocks used in this trial including the major components of each, and the addition of moisture as required.

Feedstock	Moisture added	Components
Fruit/vegetable/cardboard[1]	no	Fruit (watermelon, honeydew, rockmelon, orange, pineapple, plum, peach, persimmon, banana, apple) and vegetables (pumpkin, parsnip, shallot, bean sprout, tomato, onion, capsicum, lettuce, cabbage, carrot, corn, celery, avocado)
Mixed food organics/cardboard[1]	yes	Mixed vegetables (as above), mixed fruit (as above), bread (multi-grain bread, wholegrain bread, white rolls), meat/poultry (blood, bone, mince, fat, beef, lamb, chicken)

[1] Note that feedstocks were blended with a shredded cardboard bulking agent to achieve a C:N ratio of approximately 20-35:1.

Feedstock preparation was performed at the start of the trial. Size reduced organic components and cardboard components were measured in buckets using a platform scale (Wedderburn, Australia) and mixed by hand in tubs using a shovel or garden fork. The feedstock was prepared in small batches to allow thorough mixing of the organic and cardboard components and to more accurately represent the procedure that would be employed by an on-site vermiculture processing operation.

Pre-conditioning of feedstock was performed to enable sufficient mixing of the feedstocks and to ensure adequate structure to aid worm habitation. This pre-conditioning involved two specific steps. Firstly, the two feedstocks were blended with a cardboard bulking agent to ensure appropriate moisture contents were obtained. Results from the bench-scale trial (Recycled Organics Unit, 2000) suggested that pre-conditioning of the feedstock to achieve appropriate moisture contents is required to avoid excessive leachate production and to reduce the tendency of the units to develop anaerobic conditions. Secondly, cardboard was added to ensure the C:N ratio was maintained between 20-35:1. In this range, organic materials decompose optimally and thorough processing by the worm stock can occur (Edwards and Bohlen, 1996). The 'fist-test' (Standards Australia AS 4454, 1999) was used to qualitatively estimate this moisture content on production of the feedstock and the actual moisture content was determined using standard methods (Standards Australia AS 4454, 1999). These feedstock pre-conditioning details are shown in Table 2.2.

All feedstocks, with the exception of meat/poultry, were size reduced in a Rotary Shear shredder (Brentwood, Australia). These materials were processed to a particle size of 20 mm or less. The meat/poultry was finely minced to a particle size of 10 mm or less at the source. All materials were stored in a cool room and frozen at approximately 0 ^{o}C until used. This method of feedstock storage rendered the material free from chemical and biological change and decomposition until thawed and applied to the vermiculture units. The feedstocks were prepared and stored in this way so as to be analogous with feedstocks prepared for on-site vermiculture processing in a C&I sector organisation.

Table 2.2. Feedstock pre-conditioning including components of each feedstock, addition of cardboard bulking agent and water, bulk densities, and moisture content.

Feedstock	Components	Raw percentage composition (v/v)[1]	Mass of cardboard bulking agent (kg)[2]	Volume of water added (L)[3]	Bulk density (kg L^{-1})	Moisture content (%w/w)
Fruit/ vegetables/ cardboard	Fruit	50%	0.225	0	0.687	72.5
	Vegetables	50%				
Mixed food organics/cardboard	Fruit	30%	0.382	0.34	0.519	72.9
	Vegetables	30%				
	Bread	20%				
	Meat/poultry	20%				

[1] Raw composition prior to pre-conditioning. [2] Mass of cardboard added per kg of raw organics. [3] Volume of water added per kg of feedstock.

A representative sample of the final blended feedstock of fruit/vegetables/cardboard and mixed food organics/cardboard was analysed for a number of chemical and physical characteristics. These included moisture content, pH, electrical conductivity, organic carbon, total nitrogen, heavy metals (including Cd, Pb, Cr, Cu, Zn, Mn, Mo, Al and Ni) according to the Australian standard (Standards Australia AS 4454, 1999) and human microbial pathogens *Salmonella* spp. and *E.coli* according to the Australian standard (Standards Australia AS 1766.2.5, 1991; Standards Australia AS 1766.2.3, 1992).

Vermicast that was produced by each unit was analysed at the completion of the trial. 1 L of vermicast was sampled from each unit and pooled between replicates to obtain a representative sample. The vermicast was assessed for quality based on the parameters of pH, EC, C:N ratio, heavy metal concentration (Cd, Cr, Cu, Mn, Ni, Pb and Zn) and the presence of human microbial pathogens (*E. coli* and *Salmonella*) according to the Australian Standard (Standards Australia AS 4454, 1999). The vermicast produced was also assessed for moisture content. The initial mature vermicast used to establish the vermiculture units at the start of the trial was also analysed for pH, EC and moisture content and compared with the final vermicast produced during the trial.

At the completion of the trial, the unprocessed feedstock was removed from the unit and the worm biomass was separated from the vermicast using a motorised vermicast trommel screen (Worm Wizard, Sydney). The separated worms were weighed to determine the total worm biomass.

2.2.2 Mid-scale vermiculture units, loading of bedding, feedstocks and experimental design

Vertical loading, continuous flow vermiculture units were used in this trial to represent common commercially available vermiculture technology. Six units were used that comprised a rectangular container (0.58 × 0.92 × 0.46 m) with a surface feeding area of 0.53 m^2 and a maximum depth of 0.5 m (Figure 2.1).

The units featured a metal grating floor (50 × 50 mm square mesh) with a sliding breaker bar that allowed vermicast to be harvested. Paper was placed over the floor of the units to prevent vermicast falling through when the units were established. The paper was replaced with hessian and cardboard later in the trial as the paper was breaking down resulting in vermicast falling through the units. To overcome this problem, the 50 × 50 mm mesh was replaced with a 25 × 25 mm square mesh at the base to prevent excessive amounts of vermicast bedding falling through the units. It has been suggested by some vermiculture industry representatives that a 25 × 25 mm grid is too small resulting in difficulties at time of harvesting. However, it is the direct experience of the Recycled Organics Unit that at the depth of bedding material and feedstock compositions reported here, this grid size was required to prevent vermicast from falling through the unit into the collection tray.

A collection tray underneath the units allowed harvested vermicast and any leachate produced to be collected. Air vents were installed at the top of the units to aid airflow, and a lid provided insulation from the light. The legs of the vermiculture units were placed in buckets of water and detergent to prevent crawling pests such as ants from entering the units.

Figure 2.1. Vertical loading, continuous flow vermiculture units used in this trial.

Each unit was loaded with 150 L of mature vermicast to a depth of 0.3 m. This vermicast provided a support structure that was subsequently inoculated with 9.25 kg of Tiger worms (*Eisenia* spp.). Each unit was therefore loaded with 18.5 kg m^{-2} of worm stock. Note that this stocking rate is significantly higher than other studies (eg. 10 kg m^{-2}, Edwards, 1998) as previous results in the bench-scale trial reported that fruit and vegetables in particular, could support a higher stocking rate. With increased worm stocking rates, the rate of organic matter conversion into vermicast can be increased (Recycled Organics Unit, 2000). The mature vermicast and worm stock was purchased from a commercial worm farm (Camphor Creek Worm Farm) and was produced from pig manure.

Eisenia spp. was chosen for this trial due to this species exhibiting a wide temperature and moisture tolerance and the recognition that this species can be readily handled (Haima and Huhta, 1986; Edwards and Bater, 1992; Reinecke *et al*. 1992). The worm stock included a mixture of hatchling, juvenile and clitellate worms. A mixture of worm maturity stages was used in this trial as previous studies have shown that hatchlings and juveniles increase in biomass faster, and process more material by weight than adults (Jefferies and Audsley, 1988; Reeh, 1992).

A double layer of hessian was placed over the inoculated bedding to retain moisture within the units.

A replicated and randomised treatment design was employed to examine the decomposition of the two feedstocks. The feedstock application rates were based on the previous bench-scale vermiculture trial (Recycled Organics Unit, 2000) and utilised in this study to confirm the maximum processing capacity for fruit and vegetables, and mixed food organics in on-site vermiculture units. The feedstock loading rates for the mid-scale vermiculture trial are shown in Table 2.3.

The fruit/vegetable/cardboard feedstock was applied to the surface of the units three times per week (Monday, Wednesday and Friday) at a rate of 20.6 kg m^{-2} (30 L m^{-2}) per week, which was equivalent to 3.65 kg per unit per application.

The mixed food organics/cardboard feedstock was applied at a lower loading rate, as previous studies have shown that this feedstock is more difficult to treat in vermiculture units (Recycled Organics Unit, 2000). The mixed food organics/cardboard feedstock was applied three times per week (Monday, Wednesday and Friday) at a rate of 7.8 kg m^{-2} (15 L m^{-2}) per week, which was equivalent to 1.38 kg per unit per application.

The total number of units used in this trial was 6 (ie. 2 feedstocks $\times$ 3 replications).

Table 2.3. Loading rate per application and weekly loading rates for each feedstock.

Feedstock	Food material to cardboard mixing ratio (w/w)	Loading rate (per application)[1,2]		Maximum processing capacity	
		L m^{-2}	kg per unit	L m^{-2} wk^{-1}	kg m^{-2} wk^{-1}
Fruit/vegetable/ cardboard	4.4:1	10	3.65	30	20.6
Mixed food organics/cardboard	2.6:1	5	1.38	15	7.8

[1] The loading rate includes a cardboard bulking agent and additional moisture where appropriate (see Table 2.1). [2] Application of feedstock occurred three times per week from week 3.

Inoculated units were fed at time of establishment and once in the following week to allow a period of acclimatisation. Units were fed three times per week for the remaining 22 weeks of the trial. This regular feeding pattern was undertaken as studies have shown that regular feeding can result in high growth and reproduction rates (Reinecke and Viljoen, 1990). The units were randomly placed in the Compost Laboratory at the Recycled Organics Unit. The laboratory environment was controlled under constant fluorescent light conditions at a temperature of 20 ^{o}C.

A comprehensive monitoring regime was employed for the duration of the trial to monitor variations in unit performance for the different feedstocks. Each unit was monitored for oxygen, temperature, pH and electrical conductivity at random locations within the centre of the actively decomposing feedstock layer and 50 mm below the feeding surface. Ambient room temperature was recorded three times per week using a wall-mounted mercury thermometer. Oxygen (%O_2, v/v) and temperature (^{o}C) of the units was recorded three times per week using a combined oxygen and temperature probe (Demista, USA). The probe was inserted into the centre of the feedstock layer of each unit and also 50 mm below the bedding surface to enable two readings to be taken. These areas were chosen as regions of high worm activity and consequently the environmental conditions of these regions were monitored to ensure adequate conditions for worm habitation.

Temperature and oxygen within the vermiculture units were monitored as variations in these parameters can adversely affect worm mortality rates. Temperatures of greater than 30 ^{o}C can result in high worm mortality (Viljoen and Reinecke, 1992). The optimal temperature for the *Eisenia spp.* is 20 ^{o}C with an ideal range of 15 to 20 ^{o}C (Edwards, 1998). High temperatures within a vermiculture unit indicate an accumulation of unprocessed feedstock resulting in microbial decomposition of the material and heat generation. Worms are also sensitive to low oxygen or anaerobic conditions, reducing the effective breakdown of organic material over a period of time. Low oxygen conditions (less than 5%) can result in the production of odour within the vermiculture units due to the presence of anaerobic microorganisms (Recycled Organics Unit, 2000).

pH and electrical conductivity (EC) were monitored during the trial to ensure conditions were adequate for worm habitation. Samples of vermicast and feedstock that had been subjected to worm activity were taken from the feedstock layer and from 50 mm below the bedding surface in each unit fortnightly. A 40 mL sample from each designated area was removed and analysed for pH and EC according to standard methods (Standards Australia AS 4454, 1999). Electrical conductivity levels of less than 4 dS m^{-1} and pH in the range of 5 to 9 is considered acceptable as pH and EC can adversely affect worm survival and growth (Edwards, 1988).

The activity of the worms within each unit was monitored by visual assessment twice a week to indicate conditions within the unit. The response of worms to environmental conditions can indicate whether the units were healthy or stressed. Particular activity traits can indicate partial stresses within the vermiculture units. For example, high temperatures and decreased worm activity within the feedstock layer can indicate system stress whilst migration of the worms out of the units can indicate unit failure. Worm activity was monitored qualitatively according to criteria shown in Table 2.4.

Table 2.4. Qualitative worm activity criteria for evaluating system performance.

Category	System Performance	Diagnostic Indicator
A	No system stress – optimal/good performance	▪ Worm population mostly in feeding layer. No detrimental temperature increase (<30 ^{o}C).
B	Some system stress – moderate system performance	▪ Worm population largely in feeding layer. Some below feeding layer and some trying to escape unit indicated by worms massing around unit rim. Some detrimental temperature increase in feeding layer (>30 ^{o}C).
C1	Moderate/high system stress – sub-optimal performance	▪ Population largely around sides of unit and trying to escape through unit rim or accumulating on surface of hessian. Significant detrimental temperature increase in feeding layer (30 – 35 ^{o}C).
C2	Moderate/high system stress – sub-optimal performance	▪ Little worm population in feeding layer. Most worms feeding from underneath feeding layer. No substantial detrimental temperature increase (<30 ^{o}C).
D	System failure	▪ No worms in feedstock. Worm population extensively swarming in corners of unit or around unit rim and escaping unit.

The accumulation of feedstock within each unit was recorded once a week to monitor the rate of processing and the acceptance of each feedstock. The feedstock accumulation was monitored by measuring the depth of feedstock from the bedding surface to the feedstock surface.

The volume of leachate produced by each unit was also monitored throughout the trial. Leachate was collected in the collection tray and the volume recorded as an indication of excess moisture within each unit.

2.3 Results and discussion

2.3.1 Chemical properties of the feedstocks

Chemical properties of the raw organic components determined in the bench-scale trial (Recycled Organics Unit, 2000) are shown in Table 3.1. The chemical properties of the feedstocks for the current trial after amendment with cardboard and moisture are shown in Table 3.2. An analysis for heavy metals (including Cd, Pb, Cr, Cu, Zn, Mn, Mo, Al and Ni) and microbial pathogens (including *E. Coli* and *Salmonella*) was also conducted on the amended feedstocks with the results shown in Table 3.3.

Table 3.1: Chemical analysis of raw organic components (from Recycled Organics Unit, 2000).

Raw Feedstock	Moisture content (% w/w)	pH	Electrical Conductivity (dS m^{-1})	Organic C (% w/w)	Total N (% w/w)	C:N ratio
Cardboard	7.6	7.61	0.15	40.16	0.61	66:1
Mixed fruit	90.0	5.42	2.79	45.71	2.14	21:1
Mixed vegetables	83.2	5.37	3.19	46.28	2.11	22:1
Bread	35.2	6.15	2.46	55.12	2.42	23:1
Meat/poultry	55.4	6.22	3.48	57.89	7.49	8:1

Table 3.2. Chemical analysis of feedstocks for the current trial after cardboard amendment and moisture adjustment (as necessary).

Amended Feedstock	Moisture Content (% w/w)	pH	Electrical Conductivity (dS m^{-1})	Organic C (% w/w)	Total N (% w/w)	C:N ratio
Fruit/vegetables/ cardboard	72.5	7.01	0.778	42	0.61	69:1
Mixed food organics/ cardboard	72.9	7.53	1.671	43	1.7	25:1

Table 3.3. Heavy metal and human microbial pathogen analysis for the amended feedstocks.

Amended Feedstock	Heavy metal analysis (mg/kg)									Human microbial pathogen analysis	
	Cd	Pb	Cr	Cu	Zn	Mn	Mo	Al	Ni	***E. coli*** (MPN g^{-1})	***Salmonella* spp.** (/25 g)
Fruit/vegetables/ cardboard	<0.5	<10	<5	28	33	23	<3	5700	<5	>2400	nil
Mixed food organics/cardboard	<0.5	<10	<5	27	44	19	<3	6300	<5	>15000	nil

The *Eisenia* spp. or Tiger worm used in this trial are relatively tolerant to pH and can process feedstocks in the pH range of 5 to 9 (Edwards, 1988). The amended feedstocks used in this trial were found to have a suitable pH for processing by Tiger worms, seen in Table 3.2. The pH values for the two feedstocks were determined as 7.01 for the fruit/vegetable/cardboard feedstock and 7.53 for the mixed food organics/cardboard feedstock. The raw components of these feedstocks, particularly the fruit and vegetable components, were found to have low pH values of 5.42 and 5.37 respectively. The cardboard amendment, however, had a more neutral pH of 7.61. Thus, the cardboard amendment seemingly raised the pH of the final feedstock mixtures to a more neutral pH for processing by the worm population.

Similarly, the electrical conductivity of all feedstock components, particularly vegetables and meat/poultry, had a much higher EC value than the final amended feedstock. The cardboard amendment, with a low EC of 0.15 dS m^{-1}, lowered the electrical conductivity of the final feedstock. It should be noted, however, that all raw feedstock components, and the final feedstock mixtures, were within the desirable electrical conductivity range of less than 4 dS m^{-1} (Edwards, 1988).

The organic C, total N and C:N ratio of the amended feedstocks was determined for each feedstock. The feedstock recipes were calculated to result in a feedstock mix with a C:N ratio of 20-35:1. Table 3.2 shows that the mixed food organics/cardboard feedstock had an ideal C:N ratio of 25:1. The fruit/vegetables/cardboard feedstock, however, was found to have a C:N ratio of 69:1. This is not within the optimal range as calculated by the feedstock recipe. However, due to the relatively large particle sizes within the feedstock mixture (up to 20 mm), particularly for the cardboard component, the distribution of cardboard would have been relatively inconsistent across the entire feedstock mix. As a result, the relatively small sample of feedstock taken for organic C and total N analysis may not have been representative of the entire feedstock mix. Consequently, the high C:N ratio determined for the fruit/vegetable/cardboard feedstock may not be an accurate representation of the feedstock mix. The worm population was observed to process both feedstocks thoroughly indicating that the C:N ratio for these recipes was suitable. Nevertheless, based on the C:N ratios of the individual feedstock components, the C:N ratio for fruit/vegetable/cardboard was estimated to be 35:1.

A C:N ratio in the range of 20-35:1 is important as within this range, organic materials decompose optimally and thorough processing by the worm stock can occur (Edwards and Bohlen, 1996). Nitrogen is often considered to be the critical factor limiting earthworm survival (Curry, 1998) and hence food organics, which tend to be rich in nitrogen, can be processed well by an earthworm population under ideal conditions. To achieve such ideal conditions, carbon rich materials are blended with the organics to provide structural stability and to allow air exchange and aerobic conditions critical for worm activity and survival (Recycled Organics Unit, 1999).

The amended feedstocks used in this trial were blended at three separate times throughout the trial period and kept in a cool room until utilised. Consequently, the physical and chemical properties of these feedstocks were generally consistent across the trial. Variation in the range of raw components and the composition of the final feedstocks produced by the C&I sector would be expected due to daily variations in the production of organic material. Consequently, this variation in composition would not have resulted in alteration of the physical and chemical properties of the feedstocks. However, variation in feedstock composition would be expected for on-site vermiculture processing of C&I sector compostable organics due to daily differences in compostable materials produced on-site.

The ideal moisture content for feedstocks processed by a worm population is between 80% and 90%, with limits of 65% to 90% (Dominquez and Edwards, 1997). The moisture contents of the amended feedstocks were 72.5% and 72.9% for the fruit/vegetable/cardboard feedstock and the mixed food organics/cardboard feedstock respectively. This is considerably lower than the raw fruit and vegetable moisture contents, and consequently the addition of a cardboard bulking agent was found to successfully lower the moisture content of the amended feedstocks to a more suitable level for processing.

These lower moisture contents minimised the production of leachate from the vermiculture units. Small amounts of leachate produced were collected in the leachate collection tray (Figure 2.1) and the average weekly volume of leachate was determined for each feedstock type. The collected weekly volumes of leachate are shown in Table 3.4. The production of leachate was found to be more a result of the addition of moisture to the vermiculture units rather than as a result of moist feedstocks. Water was added to the units periodically to provide a suitable environment for the worms. Condensation on the lids of the vermiculture units was an indication of the loss of moisture from the units and problems such as the fall through of vermicast into the collection tray was an indication of the vermicast bedding being too dry.

Small quantities of leachate were produced from units treated with both feedstocks during the preliminary period. Insignificant quantities of leachate were produced in the final half of the trial, which can be attributed to the replacement of the metal grating within the vermiculture units. Water was added primarily to prevent vermicast falling through the larger size grate and consequently, after the grate size was reduced, no fall through occurred as the addition of water was decreased. The production of leachate during on-site vermiculture processing by C&I sector organisations should be avoided as leachate is high in nutrients and can produce odours resulting in pest attraction and health issues. The production of a feedstock with a suitable moisture content will minimise leachate production and result in a more efficient organics management system for on-site processing.

Results indicated that the preparation of feedstocks resulting in a suitable moisture content is critical to minimise leachate production. The formation of leachate is problematic, particularly in a commercial situation where this leachate could attract pests and requires management procedures to be implemented. Balancing the moisture content of the feedstocks with shredded cardboard is therefore essential for reducing leachate production and to ensure the bedding does not become excessively wet. Previous studies have shown that exceedingly moist feedstocks can result in very wet conditions in the bedding material, resulting in low air entry and can result in the development of anaerobic conditions (Recycled Organics Unit, 2000). Minimising the production of leachate reduces the susceptibility of the bedding to the development of anaerobic conditions, therefore eliminating potential impacts on the health of the worm population.

Table 3.4. Leachate volumes collected for each feedstock.

Feedstock[1]	Average leachate collected (L wk^{-1})	
	Preliminary period (week 1-12)	Final period (week 13-24)
Fruit/vegetables/cardboard	0.78	0.0
Mixed food organics/cardboard	0.44	0.0

[1] The volume of leachate for each replicate was pooled and the mean quantity of leachate for each treatment is represented in this table as litres (L) of leachate per week (wk^{-1}) for the duration of the preliminary period (ie. first 12 weeks of trial) and the final period (ie. second 12 weeks of the trial).

The final feedstock mixtures were analysed for heavy metals (including Cd, Pb, Cr, Cu, Zn, Mn and Mo) according to the Australian standard (Standards Australia AS 4454, 1999) and human microbial pathogens *Salmonella* spp. and *E.coli* according to the Australian standard (Standards Australia AS 1766.2.5, 1991; Standards Australia AS 1766.2.3, 1992), as shown in Table 3.3.

The analysis of raw feedstocks for microbial pathogens resulted in the detection of *E. coli* at surprisingly high levels. The fruit/vegetable/cardboard feedstock recorded *E. coli* levels at >2400 MPN g^{-1}, whilst the mixed food organics/cardboard feedstock recorded levels of >15000 MPN g^{-1}. Such high levels were not expected in these feedstocks particularly for the fruit/vegetable/cardboard feedstock. The mixed food organics/cardboard feedstock, due to the presence of meat, would be anticipated to contain some presence of *E. coli* as this bacterium is a major inhabitant of the intestinal tract of humans and other warm-blooded animals (Prescott *et al*, 1999). However, the detection of *E. coli* within the fruit/vegetable/cardboard feedstock may indicate contamination with faecal material. Due to the nature of the organic materials as waste fruits and vegetables and the nature by which this material was collected (ie. most from discards on the floor at Paddy's Market, Sydney), it is possible that contamination of the material may have occurred from soil particles or faecal material (eg. from rats). This contamination may have resulted in the high *E. coli* levels detected within the feedstocks. This interpretation is purely speculative and no analysis on the raw organic materials was performed to enable a definitive answer to why this bacterium was detected. An analysis for *Salmonella* spp. was also performed on both feedstocks, however none was detected.

2.3.2 Monitoring and system assessment procedures

In order to determine the maximum processing capacities for the feedstocks used in this trial, it was necessary to evaluate the performance of the units. A hierarchy of performance indicators has been devised that indicates the health of the vermiculture unit (Recycled Organics Unit, 2000). These indicators, in order of importance, were found to be: worm activity, the accumulation of unprocessed feedstock and chemical/environmental monitoring data (temperature, oxygen concentration, pH and EC).

Some maintenance problems were encountered in the trial due to the initial size of the metal grate floor within the vermiculture units. A mesh size of 50 × 50 mm was initially used, however, extensive fall-through of vermicast was encountered during this preliminary period. This grate was replaced by a 25 × 25 mm grate that was found to be more suitable. Consequently, during the preliminary period, the vermiculture units suffered a number of disturbances due to collapse of the bedding structure. Reconstruction of the vermiculture units was performed to amend these situations and measures were taken to minimise disturbance to the various layers within the units. These measures included removing the materials in layers: feedstock layer; intermediate layer of processing; and bedding material and replacing these layers in order. However, the column structure within the vermiculture units was undoubtedly altered and hence feeding of the units was often not performed on the days following these maintenance procedures.

The feeding schedule is indicated on the graphs of environmental monitoring data as it was anticipated that these missed feeds might have impacted on the performance of the vermiculture units. The feeding days are indicated as 'feed applied'. The application of feedstock to the vermiculture units was performed on a regular basis aside from these missed feeds. Observations have shown that the availability of food and frequency of feeding influences worm density. Previous studies have observed that the reproductive potential of the *Eisenia* spp. is influenced not only by environmental conditions but also by the quantity and availability of food (Reinecke and Viljoen, 1990). For this reason, the application of feedstock was performed regularly, however as previously discussed, some feeds were missed following maintenance procedures to allow the units to settle. This period of settling aimed to minimise stress to the units due to the accumulation of feedstock and the possible environmental problems of temperature increases and oxygen depletion.

2.3.2.1 Worm activity

Worm activity observations during the trial indicated the units were generally performing adequately. Table 3.5(a-b) summarises the weekly observations of worm activity including the category rating and the system performance.

Observations of worm activity for the fruit/vegetable/cardboard feedstock, seen in Table 3.5(a), showed that conditions within the vermiculture units varied over the trial period. Initially, the worm population was observed to be actively feeding within the feedstock layer, however, the feedstock loading rate appeared to exceed the maximum processing capacity of these units. Feedstock was found to accumulate, resulting in increased temperatures and decreased oxygen concentrations. The activity of the worms changed in response to these occurrences whereby the population redistributed to the outer edges of the feedstock where temperatures were lower. Fewer worms were observed to be actively feeding in the feedstock layer. These conditions were particularly evident during weeks 9 to 11. Consequently, the loading rate was decreased by 20% to 24 L m^{-2} wk^{-1} from day 71 (week 11). Following this decrease in loading rate, the activity of the worms slowly increased within the feedstock layer until optimal activity was observed from week 16. The feedstock was adequately processed following the loading rate reduction and the criteria for a successful vermiculture unit, according to Table 2.4, was observed for the remainder of the trial.

The observations of worm activity for the units treated with the mixed food organics/cardboard feedstock, shown in Table 3.5(b), indicated that the units were operating at an optimal level. The feedstock was processed adequately by the worm population indicating that the maximum processing capacity for this feedstock had not been reached. Consequently, the loading rate was increased by 20% to 18 L m^{-2} wk^{-1} from day 29 (week 5). Following this increase in loading rate, a small amount of feedstock was observed to accumulate, however worm activity was categorised as optimal according to Table 2.4. This system performance ranking of optimal was maintained for the remainder of the trial confirming the success of the mixed food organics/cardboard feedstock at the revised loading rate.

Table 3.5(a). Summary of weekly assessment of worm activity for the fruit/vegetable/cardboard feedstock.

Fruit/vegetable/cardboard feedstock			
Week	**Category**	**System performance**	**Comments**
1	A	Optimal	Worms actively feeding in feedstock layer
2	A	Optimal	Worms actively feeding, extensive vermicast produced
3	A	Optimal	Worms actively feeding, vermicast produced, some worms around rim
4	A	Optimal	Worms actively feeding, some worms around unit rim
5	A	Good	Some build-up of feedstock, worms active in feedstock layer
6	A-B	Good - moderate	Temperatures high (30^{o}C), worms active in feedstock layer
7	A	Good	Some build-up of feedstock, worms active in upper feedstock layer
8	A	Good	Temps high (30^{o}C), worms active in upper feedstock layer
9	A-B	Good - moderate	Temps high (30^{o}C), worms not active in centre of feedstock layer
10	A-B	Good - moderate	Temps high (30^{o}C), worms not active in centre of feedstock layer
11	A-B	Good - moderate	Decreased feedstock loading rate by 20%
12	A	Good	Worms actively feeding, vermicast produced
13	A-B	Good	Small regions of unprocessed feedstock
14	A-B	Good	Small regions of unprocessed feedstock
15	A	Good	Worms actively feeding, vermicast produced
16	A	Good - optimal	Worms actively feeding, vermicast produced
17	A	Optimal	Worms actively feeding, extensive vermicast produced
18	A	Optimal	Worms actively feeding, extensive vermicast produced
19	A	Optimal	Worms actively feeding, extensive vermicast produced
20	A	Optimal	Worms actively feeding, extensive vermicast produced
21	A	Optimal	Worms actively feeding, extensive vermicast produced
22	A	Optimal	Worms actively feeding, extensive vermicast produced
23	A	Optimal	Worms actively feeding, extensive vermicast produced
24	A	Optimal	Worms actively feeding, extensive vermicast produced

Note that the category and system performances were ranked against the criteria given in Table 2.4.

Table 3.5(b). Summary of weekly assessment of worm activity for the mixed food organics/cardboard feedstock.

Mixed food organic/cardboard feedstock			
Week	**Category**	**System performance**	**Comments**
1	A	Optimal	Worms actively feeding in feedstock layer
2	A	Optimal	Worms actively feeding, extensive vermicast produced
3	A	Optimal	Worms actively feeding, extensive vermicast produced
4	A	Optimal	Worms actively feeding, extensive vermicast produced
5	A	Optimal	Increased feedstock loading rate by 20%
6	A	Optimal	Worms actively feeding, extensive vermicast produced
7	A	Optimal	Worms actively feeding, extensive vermicast produced
8	A	Optimal	Worms actively feeding, extensive vermicast produced
9	A	Optimal	Worms actively feeding, extensive vermicast produced
10	A	Optimal	Worms actively feeding, extensive vermicast produced
11	A	Optimal	Worms actively feeding, extensive vermicast produced
12	A	Optimal	Worms actively feeding, extensive vermicast produced
13	A	Optimal	Worms actively feeding, extensive vermicast produced
14	A	Optimal	Worms actively feeding, extensive vermicast produced
15	A	Optimal	Worms actively feeding, extensive vermicast produced
16	A	Optimal	Worms actively feeding, extensive vermicast produced
17	A	Optimal	Worms actively feeding, extensive vermicast produced
18	A	Optimal	Worms actively feeding, extensive vermicast produced
19	A	Optimal	Worms actively feeding, extensive vermicast produced
20	A	Optimal	Worms actively feeding, extensive vermicast produced
21	A	Optimal	Worms actively feeding, extensive vermicast produced
22	A	Optimal	Worms actively feeding, extensive vermicast produced
23	A	Optimal	Worms actively feeding, extensive vermicast produced
24	A	Optimal	Worms actively feeding, extensive vermicast produced

Note that the category and system performances were ranked against the criteria given in Table 2.4.

2.3.2.2 Feedstock accumulation

The accumulation of unprocessed material for both feedstock types is shown in Figure 3.1. It is obvious from this figure that the fruit/vegetable/cardboard feedstock, shown in Figure 3.1(a), accumulated at a much higher rate than the mixed food organics/cardboard feedstock, shown in Figure 3.1(b). This may have been due to the higher loading rate of the fruit/vegetable/cardboard feedstock compared to the mixed food organics/cardboard feedstock. However, the loading rate for the mixed food organics/cardboard feedstock was considerably lower than the fruit/vegetable/cardboard feedstock due to the presence of high nutrient components such as meat/poultry. These high nutrient materials are recognised to be more difficult to process using vermiculture technology (Recycled Organics Unit, 2000) and hence the loading rate for this feedstock was lower.

The accumulation of unprocessed feedstock for the fruit/vegetable/cardboard feedstock at the beginning of the trial was considered to be an important indicator that the units were not successfully processing the amount of feedstock and consequently that the loading rate was too high. The average accumulation for the three replicate units for this feedstock peaked at 145 mm on day 40 (week 6) with the effects of such an accumulation including high temperatures and decreased availability of oxygen. Temperatures within the feedstock layer and bedding material were found to reach a maximum at the same time as the peak in feedstock accumulation with averages of 30 ^{o}C and 29 ^{o}C for these locations respectively on day 38 (week 6). The temperature of the feedstock material is also shown on Figure 3.1(a). Similarly, oxygen concentrations were observed to decrease significantly at this time with average concentrations of 7.7% and 7% for the feedstock layer and bedding material (Figure 3.2) respectively on day 38 (week 6). These factors resulted in an undesirable environment for the worm population that is reflected in the results in Table 3.5(a) as influencing worm activity.

Feedstock accumulation data confirmed the indications given by the observations of worm activity that the units were not operating at the optimal performance level. The loading rate was consequently decreased, as previously mentioned, by 20% on day 71 from 20.6 kg m^{-2} wk^{-1} (30 L m^{-2} wk^{-1}) to 16.5 kg m^{-2} wk^{-1} (24 L m^{-2} wk^{-1}). A sharp decrease in the amount of unprocessed feedstock within the units can be seen after this reduction in the loading rate with a minimum amount of accumulated feedstock recorded at 27 mm occurring on day 96. The depth of feedstock accumulation for the fruit/vegetable/cardboard feedstock subsequently remained at less than 80 mm for the remainder of the trial. This is significantly less than the 145 mm maximum attained during the higher loading rate, indicating that the reduced rate was more suitable. The trend, however, in feedstock accumulation at the completion of the trial appeared to be increasing indicating that the final loading rate was at the upper limit of processing capacity for this feedstock. Examination of the environmental and chemical characteristics, discussed later in this report, provided more indications on the success of this feedstock.

The mixed food organics/cardboard feedstock had a significantly lower accumulation of unprocessed feedstock. The first peak in accumulation for this feedstock also occurred on day 40 (week 6) with an average accumulation of 40 mm shown in Figure 3.1(b). A significant decrease in this accumulation occurred with feed not being applied in the first day of the following week. The subsequent minimal accumulation of feedstock, and the observations of worm activity that indicated optimal system performance, resulted in the decision to increase the loading rate from 7.8 kg m^{-2} wk^{-1} (15 L m^{-2} wk^{-1}) to 9.4 kg m^{-2} wk^{-1} (18 L m^{-2} wk^{-1}).

A peak in feedstock accumulation interestingly occurred at the same time for both feedstocks (day 40, week 6) early in the trial. This peak occurred for the mixed food organics/cardboard feedstock even though indicators of worm activity and chemical/environmental data showed these units to be performing well. It should be noted, however, that this peak in feedstock accumulation only reached 40 mm compared to 145 mm for the fruit/vegetable/cardboard feedstock. This corresponding peak for both feedstocks may indicate that a significant time period of up to six weeks is required for the vermiculture units to establish before effective processing of the feedstock can occur. This may have been due to the worm stock previously raised on a feedstock of pig manure and this period of six weeks allowed the stock to acclimatise to the new feedstock of compostable organics and cardboard. This may be significant to on-site C&I sector vermiculture processing operations whereby the introduction of feedstock to a newly established unit should be gradually introduced until the maximum processing capacity is reached. Similarly, if the feedstock composition is altered, an acclimatisation period may be beneficial to prevent feedstock accumulation and the development of potential problems such as odour production and pest attraction as a result.

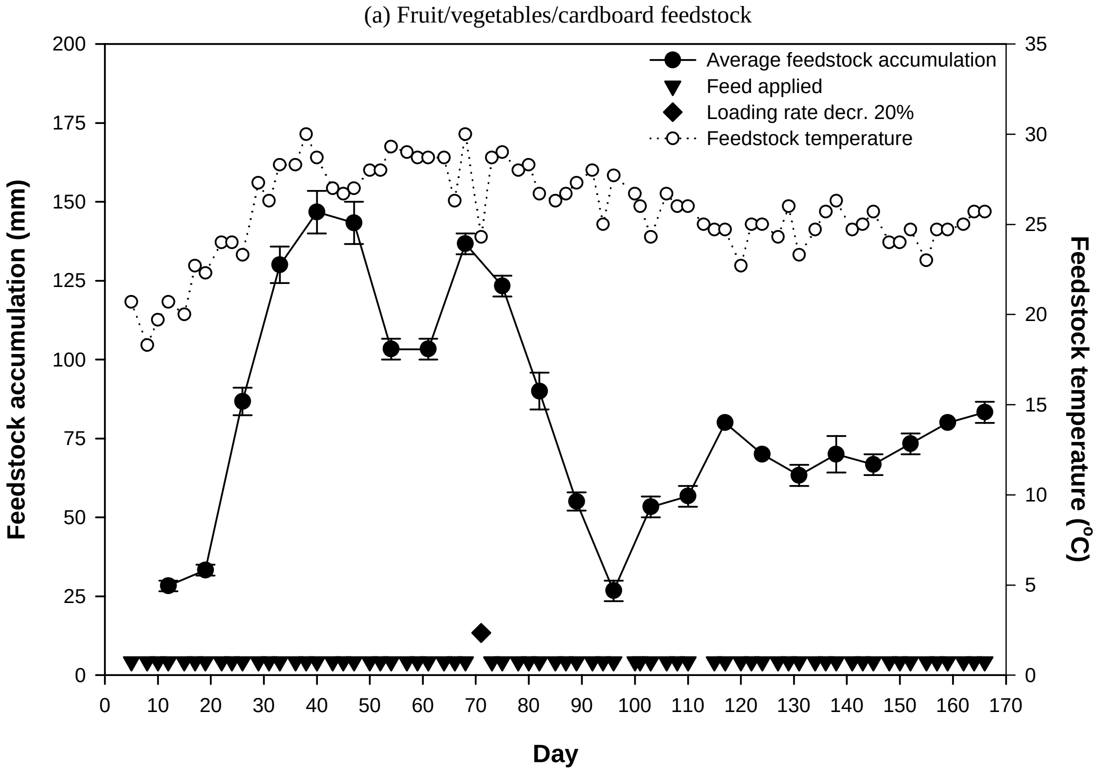
Observations of worm activity and the accumulation of unprocessed feedstock allowed evaluations of the most appropriate processing capacity to be made. The initial processing capacities used in this trial were based on those observed in the bench-scale vermiculture trial (Recycled Organics Unit, 2000). The maximum processing capacity for a fruit/cardboard feedstock and a vegetable/cardboard feedstock recommended by the bench-scale trial was 24.79 kg m^{-2} wk^{-1} (30 L m^{-2} wk^{-1}) and 24.07 kg m^{-2} wk^{-1} (30 L m^{-2} wk^{-1}) respectively. Loading rates for the current study were based on these rates, however, these loading rates were altered during the study as they were found to be unsuitable based on the observations of worm activity and the accumulation of unprocessed feedstock as discussed.

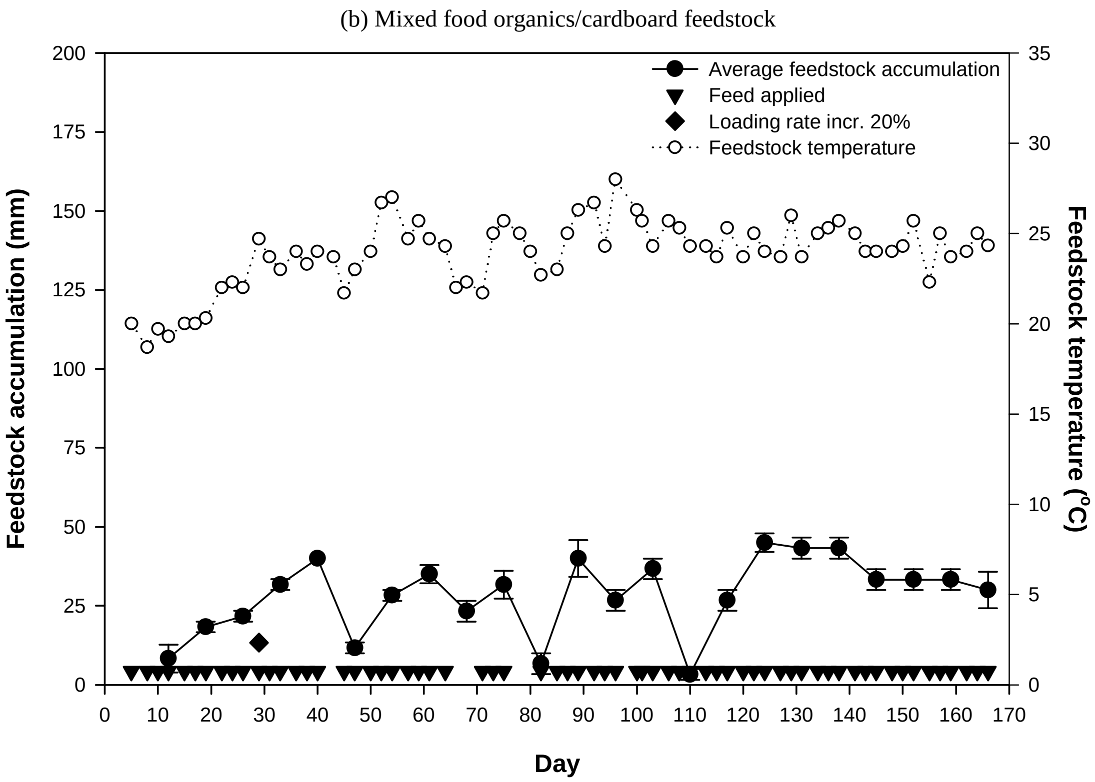
The basic components of the two feedstocks between both trials were similar, however, the actual feedstock recipes were significantly different. More importance was placed on obtaining the correct moisture content and C:N ratio in the current trial and hence this may have influenced the variation in maximum processing capacities observed. The processing capacity for the fruit and vegetable feedstocks from the bench-scale trial were observed to be at the point of failure during this study. This indicates that the suggested loading rate was too high which has been confirmed by the current study.

The mixed food organics/cardboard feedstock was also processed more successfully in the current trial than in the previous trial. This may be attributed to the improved structure of the feedstock material obtained by a greater emphasis on feedstock preparation. This improved structure was due to the increased C:N ratio through the addition of more cardboard, and a the reduction in free moisture, also due to the cardboard amendment. Feedstocks in the previous study were created to obtain a C:N ratio of exactly 20:1 which in some cases resulted in high moisture contents, ie. 90% for vegetable/cardboard, 85% for fruit/cardboard (Recycled Organics Unit, 2000). These moisture contents approached the limit of 90% for optimal vermiculture processing (Dominquez and Edwards, 1997).

The current study reduced the moisture content of the feedstocks to a more suitable level of 72% to 73%. This allowed a more structured and porous feedstock and therefore aided in preventing the development of anaerobic conditions. In effect, the decomposition of the feedstock was more controlled in this study due to the improved feedstock preparation and the provision of a feedstock more suitable for processing by a worm population. The addition of bulking agents to feedstocks has been reported as influencing the growth and reproduction of worm species possibly due to variations in organic matter content and the differing ability of bulking substrates to be digested (Dominquez *et al.* 1997). The cardboard bulking agent, used in this trial, was found to be a suitable material for vermiculture processing.

Figure 3.1. Accumulation of unprocessed feedstock for (a) fruit/vegetables/cardboard feedstock, and (b) mixed food organics/cardboard. Bars represent standard error of the mean of samples from three replicates (*n* = 3).





2.3.2.3 Temperature and oxygen

Temperature and oxygen concentrations were monitored within the areas of most worm activity, that is, the feedstock layer and 50 mm below the bedding surface. Previous studies have reported that system failure occurred whilst temperature and oxygen levels for the bedding material were within suitable ranges (Recycled Organics Unit, 2000). Monitoring temperature and oxygen within the feedstock layer, as opposed to the bedding material, provided a better indication of system performance. This is due to the feedstock layer being the most active zone for the worm population. Hence environmental characteristics for this region would more readily indicate possible system failure as opposed to the bedding material.

By monitoring both the feedstock layer and the bedding material, the variation in oxygen and temperature in relation to the presence of organic material could be investigated. The feedstock layer had a higher component of decomposing organic material whilst the bedding material would be expected to contain mostly initial (purchased) mature vermicast that was imported to establish the vermiculture units. Earthworms feed on undecomposed organic matter and accelerate the speed of organic matter decomposition (Lavelle *et al.*, 1998). The presence of decomposing organic material in the feedstock layer has the effect of increasing the temperature within this region. Heat generation during the decomposition process is almost completely derived from biological activity. Storage of this heat can occur due to the insulating effect of materials (Miller, 1993).

Oxygen concentrations within the feedstock layer were expected to decrease due to the consumption of oxygen by the earthworms and microorganisms performing the decomposition process. This decomposition process results in a net temperature increase and decrease in oxygen concentration for the feedstock layer. This is consistent with the correlation between oxygen consumption and heat evolution as a measurement of the same activity (Miller, 1993). The bedding material, however, would be expected to have a lower proportion of decomposing organic matter due to the method of surface feedstock application used in this trial. The lower depth would be expected to reduce the oxygen concentration due to a reduced rate of diffusion and the temperature would be expected to be lower than the feedstock layer due to the absence of decomposing organic material.

Significant variation was found for the oxygen and temperature data between the two feedstock types and between the two locations of monitoring for each feedstock, that is, the feedstock layer and within the bedding materials. Figure 3.2 shows temperature and oxygen concentration for the fruit/vegetable/cardboard feedstock, and Figure 3.3 shows this data for the mixed food organics/cardboard feedstock.

The temperature and oxygen data for the fruit/vegetable/cardboard feedstock showed much greater fluctuations in the feedstock material and bedding material than the mixed food organics/cardboard feedstock. The units treated with the fruit/vegetable/cardboard feedstock exhibited an initial period of relatively consistent oxygen concentrations at approximately 20%, however, after day 24 the average oxygen concentration dropped significantly to a minimum of around 8% for the feedstock layer, seen in Figure 3.2(a). The bedding layer also exhibited this decrease with a maximum oxygen concentration of approximately 20% at the beginning of the trial, dropping significantly to 11% on day 17 and continuing to decrease to a minimum of 5% on day 66, as shown in Figure 3.2(b).

A gradual increase in temperature for the fruit/vegetable/cardboard feedstock material occurred over the initial period of the trial, however, a marked increase in temperature occurred at day 29 that corresponded to the drop in oxygen for this layer. Temperature ranged from 18 to 30 ^{o}C for the feedstock material during this first stage. Consistently, the bedding material exhibited similar trends in temperature. Temperatures increased from around 20 ^{o}C at the beginning of the trial to a maximum of 30 ^{o}C on day 38 and 68 and consistently high temperatures of 27 ^{o}C to 29 ^{o}C throughout the preliminary trial period. Two slight decreases in temperature were observed that occurred directly after week 10 and week 12 with these weeks only observing one application of feedstock out of three.

The final period of the trial exhibited more consistent oxygen and temperature data for this feedstock. The loading rate was decreased on day 71 and oxygen levels for both the feedstock layer and bedding material increased significantly directly following this reduction. The feedstock layer subsequently exhibited very consistent oxygen concentrations of between 17 and 20% for the remainder of the trial. The oxygen concentrations of the bedding material were more suitable for worm habitation following this reduction in loading rate with concentrations generally above the desirable 10% for the remainder of the trial. Fluctuations in recorded data within this region may be attributed to variability in the moisture content throughout the bedding mass and the presence of anaerobic pockets within the bedding material. The temperature data for this final period was also significantly more suitable for worm habitation. The feedstock layer saw a steady decrease in temperature following the reduction in loading rate from averages of up to 30 ^{o}C to more suitable temperatures of 23 ^{o}C to 26 ^{o}C.

Overall, the temperatures for the bedding material, particularly during the preliminary period, were significantly higher than expected. The method of feedstock application involved surface feeding resulting in the organic materials placed only on the surface of the bedding. Management procedures that involved aerating the units were performed to minimise disturbance and mixing of the layers. However, the reconstruction of the vermiculture units due to the problems of the unit floors and fall-through of vermicast lead to a degree of mixing of the layers. This may have resulted in the incorporation of feedstock throughout the column and consequently the decomposition of this material at depth. The presence of this material could have contributed to heat accumulation and increased temperatures at depth. Temperatures of the bedding material during the final period stabilised after the reduction in loading rate and the absence of disturbances due to the more suitable grate size.

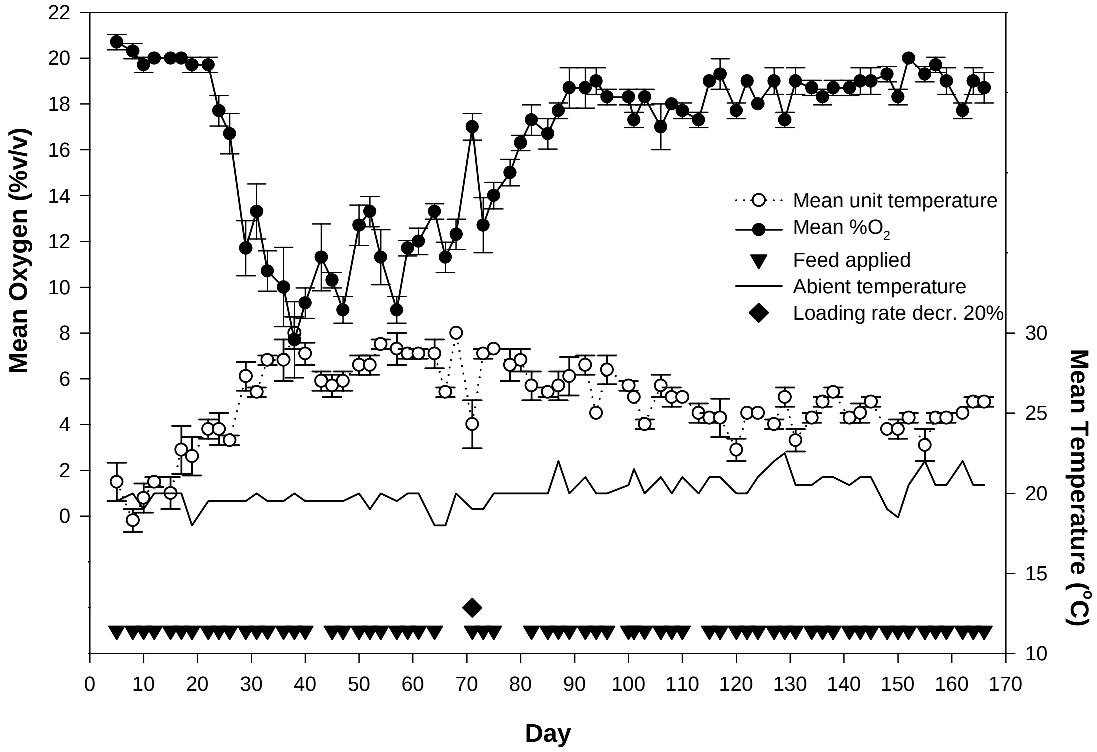
The relationship between the temperature of the feedstock material and the oxygen concentration within the material is particularly evident for the fruit/vegetable/cardboard feedstock. The maximum temperature on day 38 of 30 ^{o}C corresponded to the lowest recorded average oxygen concentration of 8%. Figure 3.2(a) clearly indicates this relationship of temperature increase and corresponding oxygen depletion. This is attributable to the accumulation of feedstock within the vermiculture unit that undergoes aerobic decomposition, resulting in oxygen consumption and heat generation (Miller, 1993). This relationship appears evident for the extremes of high temperatures and low oxygen concentrations, however, statistically no direct relationship between temperature and oxygen concentration was recorded for the trial.

During the course of the trial, the accumulation of unprocessed fruit/vegetable/cardboard feedstock resulted in the reduction in loading rate for this feedstock and the alteration of the feeding schedule. In particular during week 10, only one feed was performed on the Monday (day 64) and the units left for the remainder of the week. The following week saw a decrease of 20% in the loading rate. Figure 3.2(a) indicates that this week exhibited a significant increase in the oxygen concentration of the feedstock layer whilst the temperature decreased slightly. This may have been due to the recovery of the units from system stress due to the reduced loading rate and missed feeds.

Following the reduction in loading rate for the fruit/vegetable/cardboard feedstock, oxygen concentrations for the feedstock layer were observed to rise significantly. These concentrations remained consistently above 17% from day 87 with an average concentration of 18.5%. Similarly, the bedding material saw a rise in oxygen concentration although at a slightly later time indicating a delay in response time from this change in loading rate. This may be attributed to the time required for the worm stock to process accumulated feedstock, thus allowing diffusion of oxygen into the bedding material. The oxygen concentration in the bedding material remained at consistently higher levels than prior to the altered loading rate. An average concentration of 14 % was recorded from day 121. Similarly, temperatures for both the feedstock layer and bedding material decreased following the reduction in loading rate, with averages of 25.3 ^{o}C and 25.4 ^{o}C, respectively, for this final period (weeks 13 to 24).

Figure 3.2. Oxygen and temperature data for the fruit/vegetables/cardboard feedstock within the (a) feedstock layer, and (b) bedding material. Bars represent standard error of the mean of samples from three replicates (*n* = 3).

(a) Fruit/vegetables/cardboard feedstock – Feedstock layer



(b) Fruit/vegetables/cardboard feedstock – Bedding material

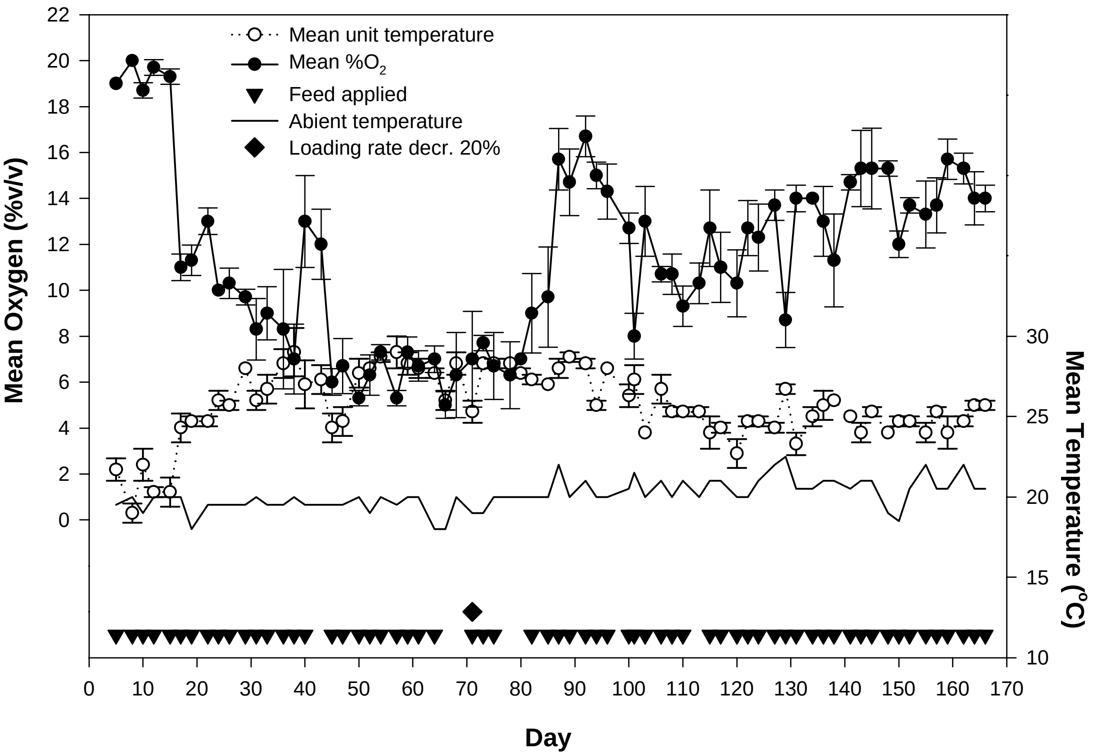
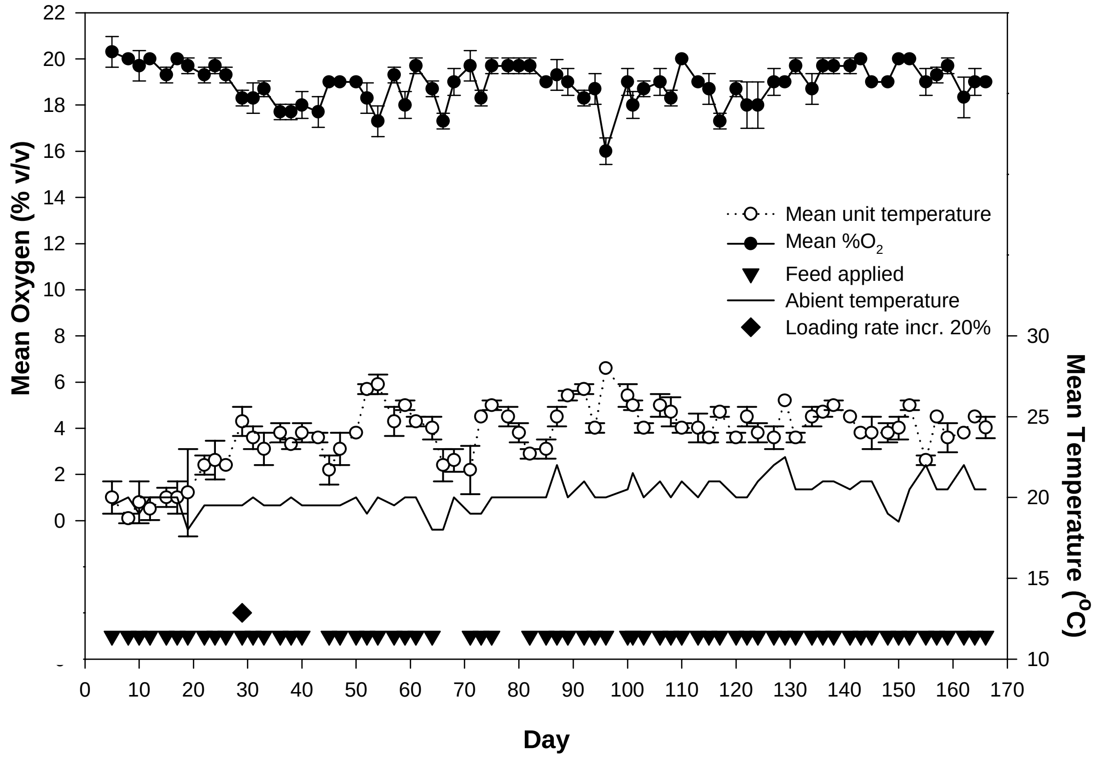
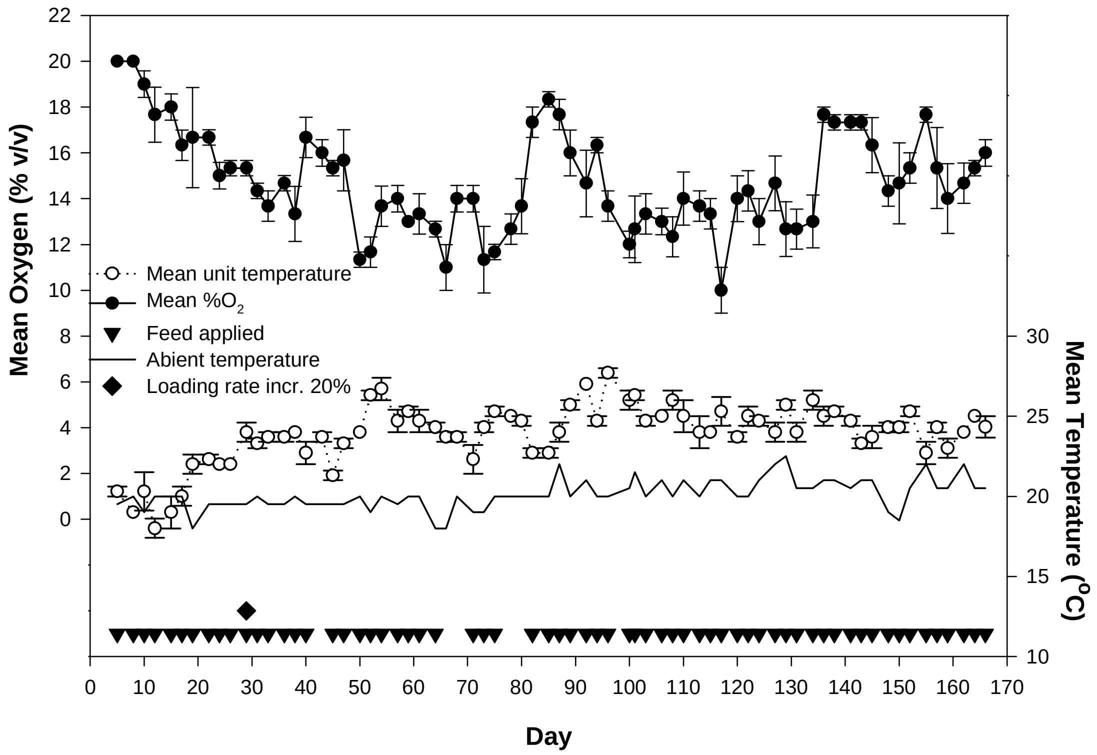


Figure 3.3. Oxygen and temperature data for the mixed food organics/cardboard feedstock within the (a) feedstock layer, and (b) bedding material. Bars represent standard error of the mean of samples from three replicates (*n* = 3).

(a) Mixed food organics/cardboard feedstock – Feedstock layer



(b) Mixed food organics/cardboard feedstock – Bedding material



The temperature and oxygen profiles for the mixed food organics/cardboard feedstock were found to be reasonably stable in the first 12 weeks of processing, and were within the optimal ranges for worm habitation. Oxygen concentrations within the feedstock layer were seen to fluctuate between 17% and 21% on average and ranged from 11% to 20% for the bedding layer. Temperatures averaged 23 ^oC for both the feedstock layer and bedding material during this preliminary period. This data is shown in Figure 3.3(b). Evidence therefore suggested that the application rate of 9.4 kg m^{-2} wk^{-1} (18 L m^{-2} wk^{-1}) of the mixed food organics/cardboard feedstock was suitable for sustainable processing of this feedstock in vermiculture units.

In contrast to the lowering of the loading rate for the fruit/vegetable/cardboard feedstock, the mixed food organics/cardboard feedstock loading rate was increased by 20% from week 5 (day 29) to 18 L m^{-2} wk^{-1}. Temperature and oxygen concentrations for the final period of the trial remained at suitable levels for vermiculture processing. Oxygen concentrations in the feedstock layer remained above 17% after the increase in loading rate with an average concentration of 19%. Similarly, the oxygen concentration of the bedding material remained above 10% with an average concentration of 14%. Generally, lower oxygen concentrations were found within the bedding material of the units treated with the mixed food organics/cardboard feedstock when compared with the feedstock layer. This is attributable to the lower depth of the bedding material resulting in decreased oxygen penetration. Temperatures, however, were higher within the feedstock layer where organic materials were decomposed by microorganisms resulting in heat generation.

Temperatures recorded for both the feedstock layer and bedding material for this feedstock remained consistently below critical levels with averages of 25 ^oC and 24 ^oC respectively. These suitable temperature and oxygen concentrations for the regions of most worm activity indicated that the increased loading rate resulted in the feedstock being processed adequately and therefore that the revised loading rate was successful.

Ambient laboratory temperature was monitored throughout the preliminary period indicated in Figures 3.2 and 3.3. This laboratory temperature exhibited only small fluctuations and ranged between 18 ^oC and 22.5 ^oC. The fluctuations in ambient temperature were not found to influence the performance of the vermiculture units in any way. However, the temperature was controlled within the trial room to prevent any outside temperature interferences from occurring. Vermiculture processing can be influenced by temperature extremes and hence measures need to be in place to prevent impacts on the worm stock during such occurrences. This trial was performed under controlled conditions to provide replicable data. The success of this trial, however, indicates that vermiculture processing in a temperature controlled environment can be performed successfully and may provide a more suitable environment. The establishment of on-site vermiculture technology may be successfully implemented in a C&I sector environment with suitable environmental considerations.

Vermicast was harvested from the units during the duration of the trial to reduce the depth of bedding material. A maximum bedding depth of 450 mm is recommended as the insulating effects of the vermicast can result in high temperatures, and compaction of the vermicast can result in low oxygen concentrations at depth (Recycled Organics Unit, 1999).

The units treated with the fruit/vegetable/cardboard feedstock were harvested during week 13 and the units treated with the mixed food organics/cardboard feedstock were harvested during week 16. Prior to this harvesting, the units increased in depth to this maximum recommended bedding thickness. Following harvesting, the bedding depth was maintained at 300 mm.

The reduction in bed thickness for the units treated with the fruit/vegetable/cardboard feedstock may have influenced the temperature and oxygen concentrations within the units by decreasing the insulating effect of the large amount of vermicast. The temperature and oxygen concentrations within the feedstock layer appeared primarily to decrease following the reduction in loading rate, however, the bedding material indicated a significant increase in oxygen following the harvesting of vermicast on day 85. Temperatures for this zone decreased more steadily following harvesting indicating that temperature is influenced less by changes in bedding thickness over short time periods. The significant increase in oxygen concentration may be attributed to the increased permeability of the bedding material allowing increased oxygen diffusion at depth. The actual process of harvesting the vermicast may have also allowed oxygen to penetrate at depth due to the mechanical disturbance of the breaker bar within the units.

The units treated with the mixed food organics/cardboard feedstock did not exhibit such a pronounced change in environmental characteristics following the harvesting of vermicast. This may have been due to the decreased rate of vermicast accumulation within these units resulting from the lower feedstock loading rate. The vermicast did not accumulate to such a depth in the units treated with this feedstock and hence less material was removed during the course of the trial.

2.3.2.4 pH and EC

pH and electrical conductivity (EC) were monitored throughout the trial for both the feedstock layer and the bedding material. Samples were taken fortnightly and analysed using standard methods (Standards Australia, 1999). Figures 3.4 and 3.5 show pH and EC data for both feedstocks.

Earthworms are thin-skinned invertebrates and have little protection from changes in the physical or chemical characteristics of the surrounding environment. Earthworms are known to be particularly sensitive to the hydrogen ion concentration, or pH, of aqueous solutions (Edwards and Bohlen, 1996). As a consequence, the surrounding environment for worms, whether it be feedstock or a bedding material, can be a factor that limits the number and distribution of the species and may even result in worm mortality. Bacteria and actinomycetes, which aid in the decomposition of organic materials, are also sensitive to low pH (Miller, 1993). Consequently, pH is an important determinant of the success of vermiculture processing. pH in the range of 5 to 9 is considered acceptable to worm populations (Edwards, 1988).

The pH ranges for the units were all well within the suitable range of 5 to 9. The lowest pH readings occurred within the bedding material at the beginning of the trial with a pH value of 6.45. The addition of the fruit/vegetable/cardboard feedstock and the mixed food organics/cardboard feedstock slightly raised the pH of the feedstock layer and bedding material over the 12 week period. A small increase in pH during the first 12 weeks was expected as during the initial stages of decomposition, ammonification, or the process of converting protein into ammonium ions (NH_4^+) occurs through bacterial action. Bacteria can then readily absorb the nitrogen for growth and cell division (Miller, 1993). However, with additional processing, it would be expected that pH would settle to approximately 7.5. Trends in pH for both feedstocks indicate that the feedstocks were within suitable pH ranges and that the vermiculture units were performing adequately. Under conditions of excessive feedstock application, anaerobic conditions can develop, leading to detrimental drops in pH to less than 5 to 6 (Miller, 1993).

The fruit/vegetable/cardboard feedstock exhibited a relatively consistent pH range in the feedstock layer with pH values recorded between 6.94 and 8.39 during the entire trial. The mixed food organics/cardboard feedstock also recorded pH values over a similar range of between 7.31 and 8.22. The minimum pH for both feedstocks was recorded at the beginning of the trial and values were then found to increase to a maximum in the preliminary period and decrease marginally to remain generally constant throughout the remainder of the trial. The pH trend found for these feedstocks reflects the predicted trend due to the process of ammonification discussed above.

The pH trend recorded for the bedding material of both feedstocks was less predictable than the feedstock material due to the reduced proportion of decomposing organic material. The bedding material consisted initially of vermicast produced from pig manure and over time saw an increase in the proportion of vermicast produced from food organics and cardboard. The initial vermicast produced from pig manure recorded a pH value of 6.45. pH was found to increase significantly above this initial value. The remainder of the trial saw fluctuations in pH readings for both feedstocks however values generally remained around a pH of 8.

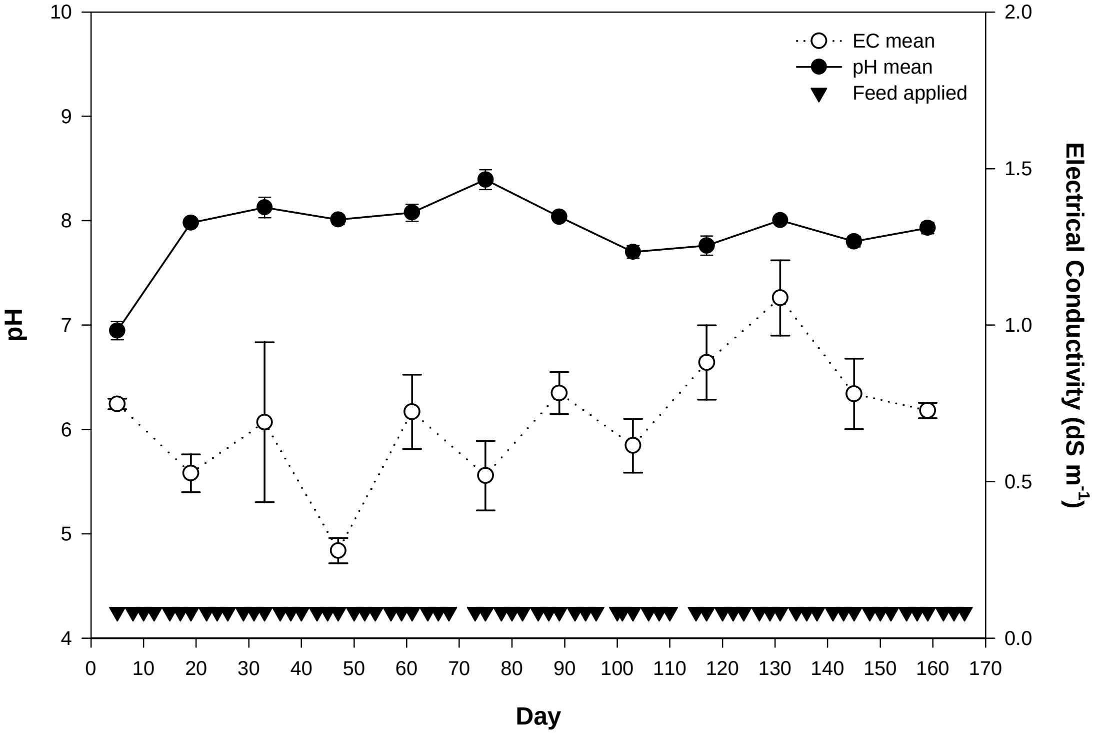
The relationship of water to earthworm survival and growth is important, as up to 85% of the fresh weight of earthworms is water (Edwards and Bohlen, 1996). Earthworms are able to maintain a relatively constant internal fluid concentration or internal osmotic pressure in dilute solutions. However, earthworms are unable to maintain this osmotic pressure in concentrated solutions and worm death can occur. EC is a measure of the salt content or osmotic stress of a solution. EC levels of less than 4 dS m^{-1} are ideal for worm habitation, however, levels exceeding this can adversely affect worm survival and growth (Edwards, 1988).

Electrical conductivity was found to be below 4 dS m^{-1} for all samples taken during the trial. The bedding material for both feedstocks in week 1 recorded a mean EC of 1.50 dS m^{-1}. EC readings for the bedding material decreased during the remainder of the preliminary period. This decrease in EC over time for the bedding can be attributed to the leaching of salts from the bedding material due to the effect of water addition and moist feedstock applications.

The collection tray at the base of the vermiculture units was observed at the completion of the trial to contain a small proportion of desiccated worms, and salt crystals were noted on the peaks of harvested vermicast left in these trays. These findings confirm the presence of salts within the leachate that had passed through the units into the collection tray. A free-draining vermiculture unit is essential to prevent accumulation of salts within the bedding material that could potential lead to worm death and system failure.

Figure 3.4. pH and electrical conductivity data for the fruit/vegetables/cardboard feedstock within the (a) feedstock layer, and (b) bedding material. Bars represent standard error of the mean of samples from three replicates (n = 3).

(a) Fruit/vegetables/cardboard feedstock – Feedstock layer



(b) Fruit/vegetables/cardboard feedstock – Bedding material

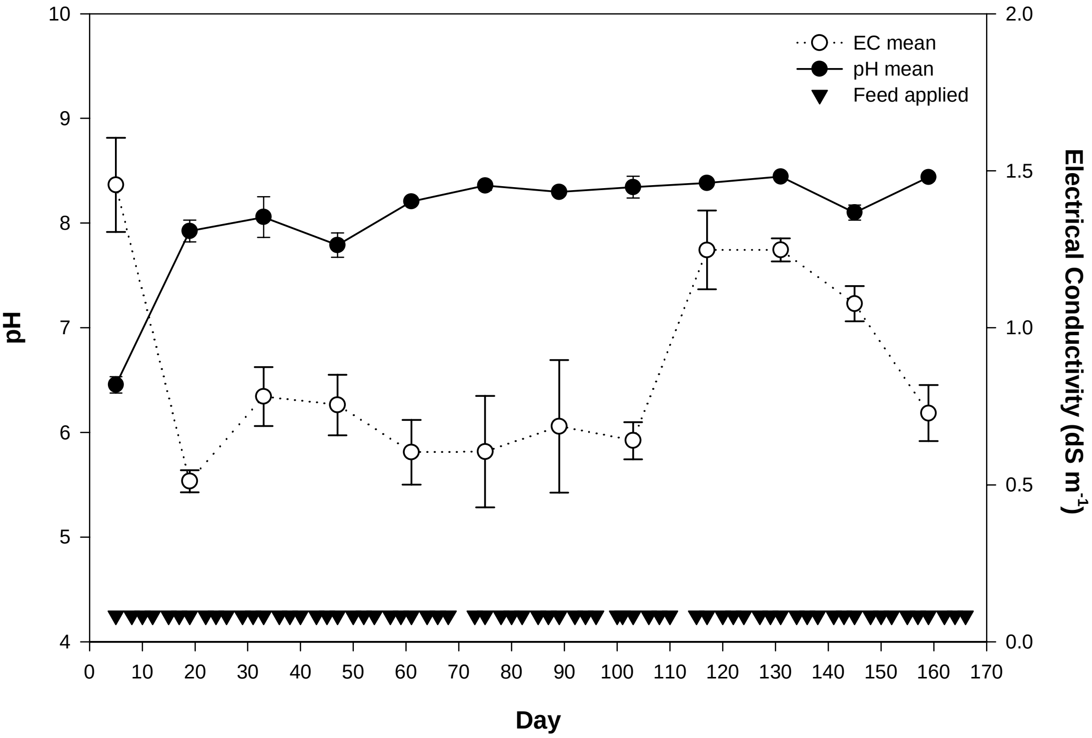
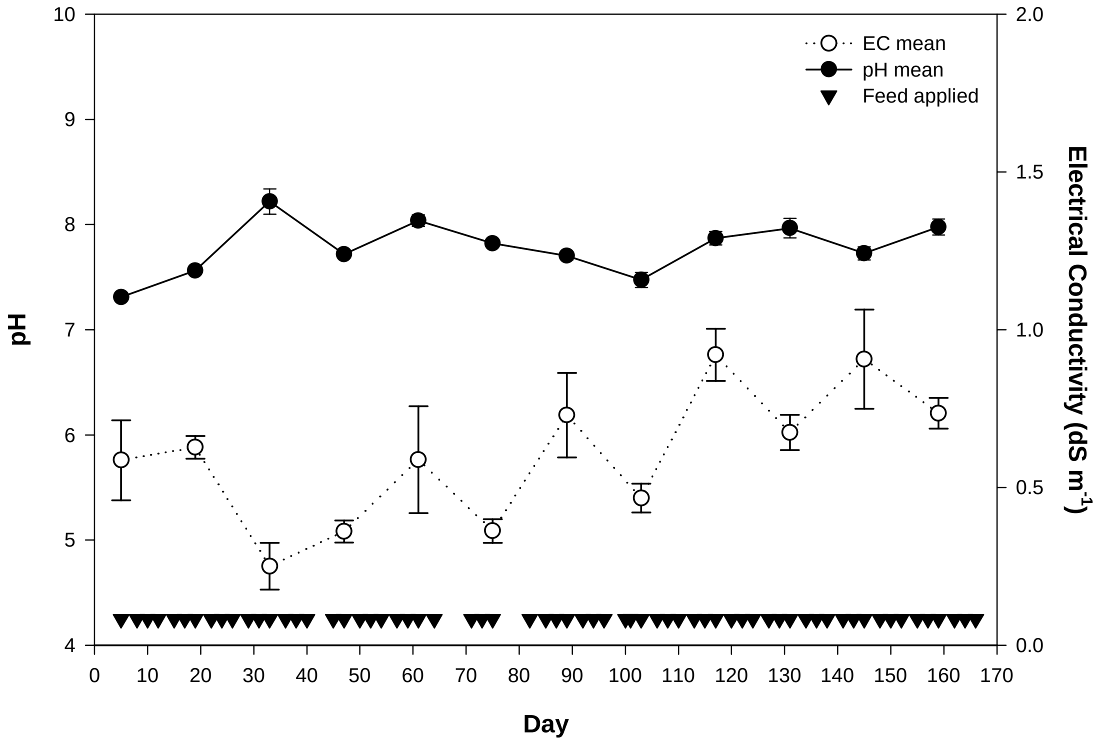
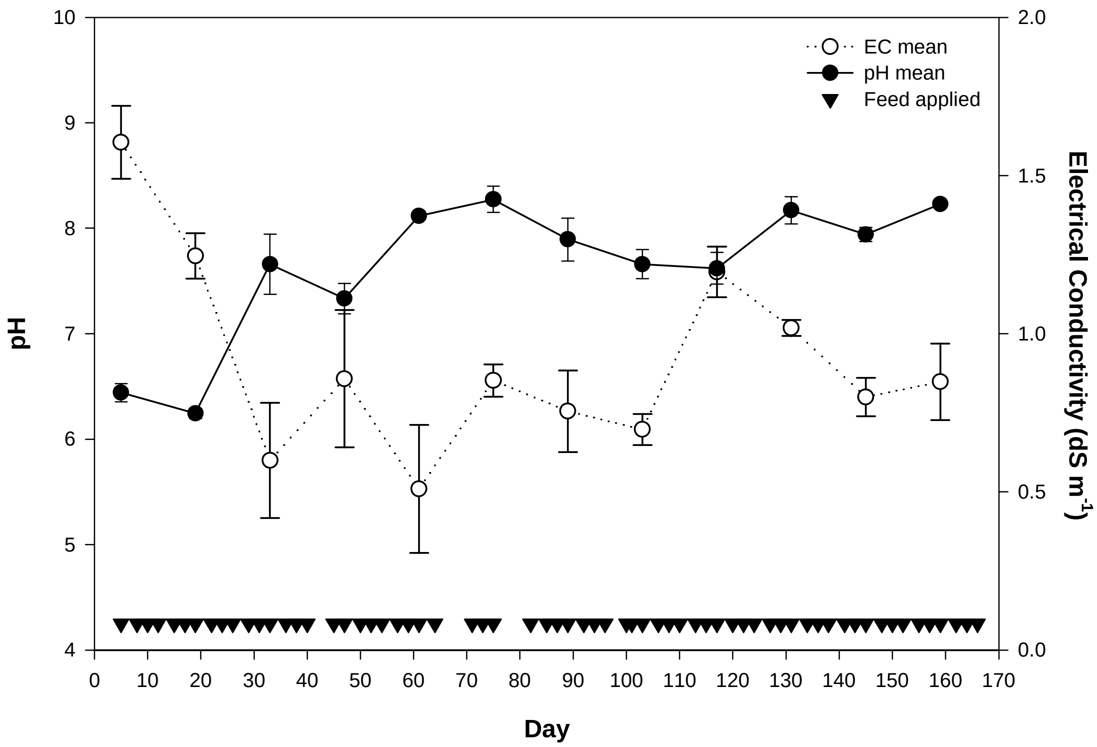


Figure 3.5. pH and electrical conductivity data for the mixed food organics/cardboard feedstock within the (a) feedstock layer, and (b) bedding material. Bars represent standard error of the mean of samples from three replicates (*n* = 3).

(a) Mixed food organics/cardboard feedstock – Feedstock layer



(b) Mixed food organics/cardboard feedstock – Bedding material



2.3.3 Worm biomass

At the completion of the trial, the worm stock and vermicast was removed from each unit and separated to determine the worm biomass. This allowed a comparison with the inoculated worm biomass of 9.25 kg per unit. Table 3.6 shows this data on worm biomass for the entire trial.

Table 3.6. Worm biomass and carrying capacity data for the feedstocks studied during the trial.

Feedstock	Inoculating worm biomass (kg)	Mean worm biomass at completion (kg)	Change in worm biomass (%)	Maximum recorded carrying capacity ($kg\ m^{-2}$ sfa*)
Fruit/vegetables/cardboard	9.25	7.90 (±1.48)	-14.59	14.91
Mixed food organics/cardboard	9.25	8.92 (±0.50)	-3.57	16.83

* sfa = surface feeding area of 0.53 m^2

Both feedstocks were found to have a reduction in total worm biomass at the completion of the trial. The process of separating the worms from the vermicast using the motorised trommel screen was found to be generally successful, however, 10% of the earthworm population was estimated to be missed in the process.

A problem encountered during the trial that may have contributed to this reduction in worm biomass was the process of harvesting vermicast. A significant quantity of vermicast was harvested during the trial, particularly from the units treated with the fruit/vegetable/cardboard feedstock. These units were found to accumulate vermicast due to the higher loading rate and consequently harvesting of the vermicast was performed to reduce the depth of the bedding within the units. Approximately 100 L of vermicast was harvested from these units during week 13, however, due to the problems associated with the metal grate at the base of the units, a significant amount of paper and cardboard was placed over the grate to prevent vermicast fall-through. Upon harvesting, worms were observed at the base of the units feeding on this source of paper and cardboard. These worms were removed from the unit with the harvested vermicast and hence an unknown worm biomass was removed mid-trial. Such a loss would not be expected for on-site units as the large quantity of paper and cardboard at the unit base was unique to the problems associated with the units used in this trial.

Harvesting of the units treated with the mixed food organics/cardboard feedstock was performed during week 16. Worm losses for these units were not anticipated as significant due to these units producing less vermicast and hence a lower quantity of material was harvested. A smaller population of worms was observed at the base of units treated with this feedstock indicating that less worms were harvested with the vermicast.

In consideration of the problems encountered during the trial, the reduction in worm biomass is relatively low. The units treated with the mixed food organics/cardboard feedstock displayed a relatively consistent worm biomass across the three replicates and a reduction in worm biomass of less than 4%. This result indicates that the worm population may have been inoculated at the maximum carrying capacity of the units as recommended by the previous trial (Recycled Organics Unit, 2000) and the small decrease was indicative of slight variation around this maximum population density.

The units treated with the fruit/vegetable/cardboard feedstock displayed a more variable reduction in worm biomass across the replicates and a lower average biomass at the completion of the trial. A decrease of almost 15% in worm biomass from the inoculated biomass was recorded. However, in consideration of the large quantity of vermicast harvested and the associated problems with the unit design, this reduction may not be entirely indicative of the success of the feedstock.

The reduction in worm biomass for the current trial in comparison with the preceding trial (Recycled Organics Unit, 2000) may also be attributed to the variation in feedstock composition. The previous trial utilised feedstocks with a much higher organics content to bulking agent than the current trial. This was due to the current trial exhibiting a greater focus on achieving a suitable C:N ratio of 20-35:1. This increased C:N ratio resulted in a significantly higher cardboard content within the feedstock and consequently a reduction in the nutritional value of the material. This reduction in nutrient content, however, was necessary to control the moisture content of the feedstock and prevent the associated problems of decreased porosity and oxygen penetration that can result in anaerobic conditions and ultimate system failure.

The C:N ratio determined for the fruit/vegetable/cardboard feedstock was found to be 65:1 (actual C:N based on C:N of individual components was 35:1), much higher than the anticipated 20-35:1. Although it is possible that this was not an accurate representation of the entire feedstock composition, this may have been a cause of the decrease in worm biomass for the trial. Conversely, the mixed food organics/cardboard feedstock was found to have a C:N ratio of 25:1 resulting in a higher nutrient content for this feedstock. This may have been a contributing factor to the higher worm biomass for this feedstock as opposed to the fruit/vegetable/cardboard feedstock.

A comparison was made between the worm biomass at the completion of the trial with the calculated worm biomass for the previous bench-scale trial (Recycled Organics Unit, 2000). The previous trial examined feedstocks consisting of fruit/cardboard and vegetables/cardboard whereas the current trial combined these organics to create the fruit/vegetable/cardboard feedstock. This was performed as the combined feedstock would represent the type of organics that would typically be produced by an on-site C&I sector organisation such as a supermarkets.

The determined worm carrying capacity at the completion of the previous trial was calculated as 18.5 kg m^{-2} for the fruit/cardboard feedstock and 12.3 kg m^{-2} for the vegetable/cardboard feedstock. These feedstocks, however, are not directly comparable with the fruit/vegetable/cardboard feedstock evaluated in the current trial. As previously discussed, the cardboard component of the feedstocks in the current trial was increased to control moisture content and the production of leachate. Consequently, the organic component of the final feedstock mixture was reduced. This reduction in nutrient content for the feedstock in the current trial may have resulted in the decrease in worm biomass for this feedstock. The carrying capacity for the current trial of 14.91 kg m^{-2} for the fruit/vegetable/cardboard feedstock falls between the rates found for the fruit and vegetable feedstocks in the previous trial. However, due to the high variation in feedstock recipe this may not be directly comparable.

The carrying capacity of the mixed food organics/cardboard feedstock in the current trial, 16.83 kg m^{-2}, was found to be consistent with findings of the previous trial of 16.8 kg m^{-2}. However, the feedstock recipe between the two trials was significantly different due to the increased proportion of cardboard.

2.3.4 Chemical properties of the vermicast

At the completion of the trial, vermicast was sampled from each unit and analysed for heavy metals and microbial pathogens. The samples of vermicast were taken from the replicates of each feedstock and pooled to obtain a representative sample of the product. The chemical analysis of the initial vermicast used to inoculate the units and the final vermicast produced from each feedstock is shown in Table 3.7.

The moisture contents for the final vermicast produced from the two feedstocks were found to be 76.6% for the fruit/vegetable/cardboard feedstock and 73.7% for the mixed food organics/cardboard feedstock. These moisture contents are generally consistent with the previous trial, however, moisture contents for the feedstocks were considerably lower in the current trial than the previous trial. This resulted in the production of leachate in the current trial being largely avoided due to the higher proportion of bulking agent within the feedstock. This increased cardboard component and reduced feedstock moisture content did not alter the moisture content of the final vermicast product. The final vermicast therefore resulted in a product suitable for worm habitation and the increased cardboard content reduced the excessive volumes of leachate encountered in the previous trial that creates additional work for operational staff.

Table 3.7. Chemical analysis of initial vermicast and final vermicast product from each feedstock.

Feedstock	Moisture content (%w/w)	pH	Electrical conductivity (dS m^{-1})	*E. Coli* *MPN g^{-1}	*Salmonella spp.* /25 g	Organic C (%w/w)	Total N (%w/w)	C:N ratio
Initial	n.d.	6.45	1.530	n.d.	n.d.	n.d.	n.d.	n.d.
FV/C	76.6	8.12	1.359	<30	nil	36	1.8	20:1
MFO/C	73.7	7.23	1.449	150	nil	32	2.0	16:1

Note: A 1 L sample of vermicast was taken from the replicates of each feedstock, pooled and mixed; initial = mature vermicast used to establish units prior to trial commencing (this vermicast was purchased from a commercial worm farm and was produced from pig manure); FV/C = fruit/vegetables/cardboard; MFO/C = mixed food organics/cardboard; n.d. not determined; * Mean Probable Number.

The pH of the final vermicast varied significantly from the initial vermicast used to establish the units. This initial vermicast was purchased from a commercial worm farm and was produced from pig manure. The pH of this initial vermicast was found to be 6.45, much lower than the final vermicast produced from the feedstocks used in this trial. The vermicast produced from the fruit/vegetable/cardboard feedstock had a pH of 8.12 and the vermicast produced from the mixed food organics/cardboard feedstock had a pH of 7.23. The electrical conductivity was found to be generally consistent for the initial and final vermicast. The initial vermicast recorded the highest EC level of 1.530 dS m^{-1} with the final vermicast recording 1.359 dS m^{-1} and 1.449 dS m^{-1} for the fruit/vegetable/cardboard feedstock and mixed food organics/cardboard feedstock respectively. These EC levels are all below the recommended maximum level of 4 dS m^{-1} (Edwards, 1988).

The microbiological analysis detected no presence of *Salmonella* spp. in the final vermicast produced from the two feedstocks. This is consistent with the absence of *Salmonella* spp. in the raw feedstocks prior to vermiculture processing as reported in Table 3.3.

E. coli, however, was detected in the vermicast produced from both feedstocks at levels of <30 and 150 MPN g^{-1} for the fruit/vegetable/cardboard feedstock and mixed food organics/cardboard feedstock respectively. This is a significant decrease in pathogen levels from the raw feedstock prior to processing in the vermiculture units.

The raw fruit/vegetable/cardboard feedstock was found to contain *E. coli* at levels of >2 400 MPN g^{-1} whilst the mixed food organics/cardboard feedstock detected levels of >15 000 MPN g^{-1}. This significant reduction in pathogen levels indicates the ability of vermiculture processing to reduce human microbial pathogen levels. The pathogen suppression ability of earthworms has been well demonstrated by previous studies (Brown and Mitchell, 1981; Amaravadi *et al*, 1990; Pederson and Hendrikson, 1993) and was evident in this trial. The sampled vermicast was taken directly from the vermiculture units prior to any form of maturing. A maturation phase is common for harvested vermicast to increase pathogen suppression within the material. The significant reduction in *E. coli* merely as a result of earthworm processing indicates the success of this type of organics management system. Maturing the vermicast would also improve the quality of the final product for landscaping purposes.

The *E. coli* levels detected in the vermicast produced from the mixed food organics/cardboard feedstock (>100 MPN g^{-1}) would render the material as stabilisation grade B according to the Environmental Guidelines for Use and Disposal of Biosolids Products (NSW EPA, 1997).

The C:N ratio of the final vermicast produced from both feedstocks was found to vary from the feedstock mixtures. This is consistent with the reports from Edwards and Bohlen (1996) that earthworms can alter the C:N ratio of material that passes through their digestive tract. The C:N ratio of the fruit/vegetable/cardboard feedstock was found to be 69:1, however, as previously discussed this result may not have been indicative of the entire feedstock recipe. The C:N ratio of the vermicast produced from this feedstock was 20:1. Similarly, the vermicast produced from the mixed food organics/cardboard feedstock exhibited a decrease in the C:N ratio from 25:1 for the feedstock to 16:1 for the vermicast. These results are consistent with reports that have found a lower C:N ratio for vermicast produced when earthworms were fed feedstocks with a higher C:N ratio. However, such a comparison of the C:N ratio of earthworm casts to that of feedstock does not always provide a valid assessment of the influence of earthworms on the C:N ratio of the ingested feedstock. This is due to the difficulties in determining the exact composition of the ingested material (Edwards and Bohlen, 1996).

A total nitrogen content of greater than or equal to 0.8% (dry weight basis) is required if the product is claimed to contribute to plant nutrition according to the Australian Standard AS 4454 (1999). Both vermicast products meet this requirement for total nitrogen. Australian Standard AS 4454 (1999) for composts, soil conditioners and mulches no longer specifies a C:N ratio however it can still be a useful guide to the maturity of the product. A C:N ratio of ≤20:1 is desirable if the product claims to contribute to plant nutrition. The vermicast produced from the mixed food organics/cardboard feedstock complies with this low C:N ratio.

The final vermicast produced from the two feedstocks was also analysed for the presence of heavy metals. Heavy metal contamination is important for designating the use of vermicast as a product for landscaping purposes. The presence of the heavy metals Cd, Pb, Cr, Cu, Zn, Mn, Mo, Al and Ni within the final vermicast is shown in Table 3.8.

Table 3.8. Heavy metal analysis of final vermicast product from each feedstock.

Feedstock	Heavy metal concentrations (mg/kg)								
	Cd	**Pb**	**Cr**	**Cu**	**Zn**	**Mn**	**Mo**	**Al**	**Ni**
FV/C	<0.5	<10	13	55	160	630	<3	13000	11
MFO/C	<0.5	<10	15	51	210	1000	<3	12000	8

Note: A 1 L sample of vermicast was taken from the replicates of each feedstock, pooled and mixed; FV/C = fruit/vegetables/cardboard; MFO/C = mixed food organics/cardboard.

Compliance with the Australian Standard for a soil conditioner product such as vermicast requires that all materials shall fully comply with the heavy metals provisions of guidelines for use and disposal of biosolids products that are for unrestricted use (Standards Australia AS 4454, 1999). The vermicast products met the requirements for Cu, Zn, Mo, Cd, Cr, Ni and Pb. However, Al and Mn levels were high in both products. The final vermicast exhibited some change in heavy metal content in comparison to the feedstock materials. Cd, Pb and Mo levels were unaltered and Cr, Cu and Ni levels increase slightly in the final vermicast product. Zn, Mn and Al increased significantly in the final vermicast product when compared with the feedstock heavy metal analysis (Table 3.3). This may have been due to high levels of these heavy metals present in the initial mature (purchased) vermicast, however this initial vermicast was not analysed.

2.3.5 Revised loading rates and maximum processing capacities of feedstocks

As discussed, a series of indicators were used to describe the performance of the vermiculture units. These indicators included: worm activity, accumulation of unprocessed feedstock and chemical/environmental monitoring data (temperature, oxygen concentration, pH and EC).

The loading rates for the feedstocks used in this study were based on findings from the bench-scale vermiculture trial (Recycled Organics Unit, 2000). The initial loading rate for the fruit/vegetable/cardboard feedstock was recommended as 20.6 kg m^{-2} wk^{-1} (30 L m^{-2} wk^{-1}). However, the performance indicators used to assess the success of this loading rate observed that the units were unable to process this loading rate adequately. Indications of system failure were evident through worm activity, an accumulation of unprocessed feedstock, increasing temperatures and subsequently decreasing oxygen concentrations within the vermiculture units. As a result, the loading rate was decreased by 20% from the initial rate to 16.5 kg m^{-2} wk^{-1} (24 L m^{-2} wk^{-1}).

The mixed food organics/cardboard feedstock, on the other hand, showed optimal system performance based on the indicators of performance. These indicators included minimal unprocessed feedstock accumulation, and temperature and oxygen concentrations within the ideal ranges. The loading rate for this feedstock was consequently increased by 20% from an initial rate of 7.6 kg m^{-2} wk^{-1} (15 L m^{-2} wk^{-1}) to 9.4 kg m^{-2} wk^{-1} (18 L m^{-2} wk^{-1}). This increase was performed to ensure that the maximum processing capacity was reached and to allow an evaluation of the suitability of vermiculture processing for treating a feedstock of mixed food organics/cardboard.

The initial and final daily and weekly loading rates for these feedstocks are shown in Table 3.9. The final loading rates for the two feedstocks were found to be suitable for on-site vermiculture processing. The increased focus on feedstock preparation by obtaining a suitable moisture content and porosity through increased cardboard amendment seemingly produced a feedstock that can be readily treated using vermiculture technology. However, the recommendation of the above loading rates can only be given if the high degree of feedstock preparation is enforced as well as management procedures for ensuring a healthy vermiculture unit.

The final loading rate for the fruit/vegetable/cardboard feedstock of 16 kg m^{-2} wk^{-1} was found to be sustainable throughout the duration of this trial. However, some feedstock was found to accumulate within the units indicating that thorough processing, particularly of the cardboard component, may not have been performed. However, observations of worm activity and chemical/environmental characteristics indicated that the units were performing well. Consequently, it may be interpreted that the cardboard component for this feedstock was at the maximum recommended level. Exceeding this proportion of cardboard may exceed the processing capacity of this feedstock and this could ultimately result in problems. The organics to cardboard ratio of 4.4:1 (w/w) is therefore recommended as suitable, and any alterations to this should be performed with caution, particularly when increasing the cardboard component.

The mixed food organics/cardboard feedstock was readily processed in the on-site units at a loading rate of 9.4 kg m^{-2} wk^{-1}. Minimum feedstock accumulation was observed and worm activity was characterised as optimal. Observations of the decomposition of the meat/poultry component indicated that the composition of the feedstock should not be altered in any way that would result in the increase in proportion of this component. Fat within the meat/poultry raw material was processed at a slower rate than the remaining components although it was processed entirely over time. The proportion of this component should not be increased as problems such as odour development and incomplete processing may occur.

Table 3.9. Revised loading rates per application and weekly loading rates for each feedstock.

Feedstock	**Food material to cardboard mixing ratio (w/w)**		**Loading rate (per application)[1,2]**		**Loading rate (per week)[1]**	
			L m^{-2}	**kg per unit**	**L m^{-2} wk^{-1}**	**kg m^{-2} wk^{-1}**
Fruit/vegetable/ cardboard	4.4:1	Initial loading rate Week 1-10	10	3.65	30	20.6
		Final loading rate Week 11-24	8	2.92	24	16.5
Mixed food organics/cardboard	2.6:1	Initial loading rate Week 1-4	5	1.38	15	7.8
		Final loading rate Week 5-24	6	1.66	18	9.4

[1] The loading rate includes a cardboard bulking agent and additional moisture where appropriate (see Table 2.1). [2] Application of feedstock occurred three times per week from week 3. Initial loading rates were altered and the final loading rates were found to be more successful at the completion of the trial.

2.3.6 Maximum processing capacities of feedstocks

2.3.6.1 Determining the maximum processing capacity

Determining the maximum processing capacity of the feedstocks used in this trial is important to allow C&I sector organisations to determine whether vermiculture processing is a viable option for on-site treatment of compostable organic materials. Processing capacity is the maximum gross mass of a feedstock (kg) that can be applied per unit area (m^2) per unit time to a vermiculture unit under managed environmental conditions (Recycled Organics Unit, 2001a). Processing capacity can vary according to environmental conditions, feedstock loading rates, variation in feedstock composition, worm species and carrying capacity.

In order to determine the maximum processing capacities of the two feedstocks investigated in this trial, the units needed to reach approximate steady-state conditions. The preliminary period of this trial consisting of 12 weeks, was found to be inadequate for steady state conditions to be reached. Figure 3.6 shows that the temperatures for the feedstocks in both the feedstock and bedding layers were not steady but were increasing after 12 weeks and had therefore not fully stabilised. The fruit/vegetable/cardboard feedstock can be seen to have reached unsuitable temperatures and that the general trend was increasing. System failure would be imminent if this situation was left unaltered. Similarly, the oxygen concentrations of the feedstock and bedding layers had not reached reasonable steady-state conditions and were in fact continuing to decrease with time, shown in Figure 3.7. These low oxygen levels would also tend to indicate system failure would occur. The mixed food organics/cardboard feedstock also showed slight increases in temperature and decreases in oxygen concentrations although not as pronounced as the fruit/vegetable/cardboard feedstock. The altered loading rates for these feedstocks required a longer time period to determine whether or not the revised rates would result in suitable processing of the feedstock or if system failure was possible.

The trial was subsequently extended for a further 12 weeks to provide a longer processing period and to allow the units more time to reach steady state conditions and therefore confirm viability of loading rates. The final 12 weeks of the trial exhibited more consistent data for temperature and oxygen concentrations. Figures 3.8 and 3.9 show that temperatures for this final 12 weeks were more stable and decreased over this time period from the high temperatures reached during the preliminary period. Similarly, oxygen concentrations became more stable in this final period and increased to more suitable levels. The attainment of these more suitable conditions is particularly evident for the fruit/vegetable/cardboard feedstock. The general trend for temperature over this final period in both the feedstock and bedding material shows a significant decline over time. Similarly, oxygen concentrations increased in both layers resulting in a more habitable environment for the worm population. The variation in both temperature and oxygen concentration is reduced during this final period indicated by the more consistent data around the trendline. The preliminary period showed inconsistency in temperature and oxygen with numerous peaks and troughs whilst the final data set indicates that the units had reached a more uniform or steady state of processing.

The entire data set for temperature and oxygen concentration trends are shown for both feedstocks in Figures 3.10 and 3.11. The significant variation between the preliminary period and the final period is evident in these graphs. A higher degree of steadiness is evident for the final period indicating that the final loading rates were more appropriate. This final period also observed temperatures and oxygen concentrations that consistently fell within optimal limits for vermiculture processing.

2.3.6.2 Quantification of maximum processing capacity

The maximum processing capacity for the two feedstocks utilised in this trial are shown in Table 3.10. These processing capacities are the revised loading rates confirmed during the final period of the trial.

The maximum processing capacity, including the cardboard amendment, for the fruit/vegetable/cardboard feedstock was found to be 16.5 kg per m^2 of surface feeding area per week (kg m^{-2} wk^{-1}). This is equivalent to 13.4 kg m^{-2} wk^{-1} of unamended fruit and vegetable materials (ie. without cardboard amendment).

The maximum processing capacity of the mixed food organics/cardboard feedstock was found to be 9.4 kg m^{-2} wk^{-1}. This is equivalent to 6.8 kg m^{-2} wk^{-1} of mixed food materials (ie. without the cardboard amendment).

2.3.6.2 Worm biomass required

The worm biomass required at the time of unit establishment is given in Table 3.10 as 14.9 kg m^{-2} for the fruit/vegetable/cardboard feedstock and 16.8 kg m^{-2} for the mixed food organics/cardboard feedstock. This worm biomass required at inoculation was determined based on the final worm biomass attained at the completion of the trial. This quantity of worms is recommended to establish a sustainable worm population at the commencement of the processing operation. As previously discussed, it is recommended that a period of acclimatisation is provided for the worm stock in the new vermiculture units and particularly if the worms were previously processing a different feedstock as was the case in this trial.

Table 3.10. Maximum recorded processing capacities for the feedstocks detailing the processing capacity of blended feedstock material, the proportion of raw organic material and the quantity of worm biomass required to inoculate a vermiculture unit to treat these feedstocks.

Feedstock	Worm biomass required at inoculation to maximise processing capacity (kg m^{-2})	Maximum processing capacity of amended feedstock[1] (kg m^{-2} wk^{-1})	Maximum processing capacity of organic component[2] (kg m^{-2} wk^{-1})
Fruit/vegetable/cardboard	14.9	16.5	13.4
Mixed food organics/cardboard	16.8	9.4	6.8

[1] Maximum processing capacity of final feedstock after amendment with cardboard bulking agent per m^2 of surface feeding area per week. [2] Maximum processing capacity of the organic component of the feedstock when applied as amended feedstock per m^2 of surface feeding area per week.

The maximum processing capacities determined in this trial were significantly lower than the previous trial. The maximum processing capacity of the fruit/cardboard feedstock in the previous trial was recommended as 24.79 kg m^{-2} wk^{-1} (ie. 23.66 kg m^{-2} wk^{-1} of unamended fruit) (Recycled Organics Unit, 2000). This is significantly higher than the current trial where the maximum processing capacity for the fruit/vegetable/cardboard feedstock was found to be 16.5 kg m^{-2} wk^{-1} (ie. 13.4 kg m^{-2} wk^{-1} unamended fruit and vegetables). This reduction may be attributed to the increased cardboard component of the feedstock in the current trial resulting in a lower nutrient content. This increased cardboard component was necessary to achieve a more suitable structure for the final feedstock mixture and to absorb excess moisture from the organic component. The production of little or no leachate for the duration of the trial indicates that this increased cardboard component and subsequent improved feedstock composition can reduce the need for leachate collection and disposal that in some situations may cause undesirable problems such as odour production. Additionally, it was observed in the previous trial that units treated with this feedstock were approaching system failure due to the high moisture content and poor structure of the feedstock whereas the performance indicators utilised in the current trial indicated these units to be operating at an optimal level.

The mixed food organics/cardboard feedstock was also found to process the feedstock at a lower rate in the current trial when compared to the previous trial. The previous trial recorded a maximum processing capacity of 9.95 kg m^{-2} wk^{-1} (ie. 9.52 kg m^{-2} wk^{-1} unamended mixed food organics) (Recycled Organics Unit, 2000). This is relatively consistent with the maximum processing capacity of the feedstock for the current trial of 9.4 kg m^{-2} wk^{-1}, however, when considering only the unamended mixed food component, the maximum processing capacity was 6.8 kg m^{-2} wk^{-1}. Again, the feedstock processed in the current trial was observed to have an improved structure and moisture content when compared to the previous trial, due to an increased cardboard content. The performance indicators rated those units processing the mixed food organics/cardboard feedstock as optimal for the entire duration of the current trial.

The quantity of compostable organics that can be successfully processed using vermiculture technology has seemingly decreased for the current trial in comparison to the previous trial. This is indicated by the reduction in maximum processing capacity for the current trial and the decreased food organic component. However, the performance indicators utilised in both trials confirmed the overall performance of the feedstocks in the current trial to be sustainable. This was evident due to the optimal worm activity within the units, the general absence of unprocessed feedstock and the suitable environmental and chemical characteristics of the units for the duration of the trial.

Although a decreased quantity of feedstock was processed, the complete absence of system stress indicates that the final loading rates are sustainable. The implementation of sustainable loading rates is essential for the prevention of system stress leading to undesirable problems common in vermiculture processing. Avoiding these potential problems is critical for the successful installation of an on-site vermiculture processing operation in a C&I sector organisation.

Figure 3.6. Average temperature gradients for the fruit/vegetable/cardboard (FVC) feedstock and mixed food organics/cardboard (MFOC) feedstock for the centre of the feedstock layer (COF) and 50 mm below the bedding surface (BBS) during the preliminary period (weeks 1-12).

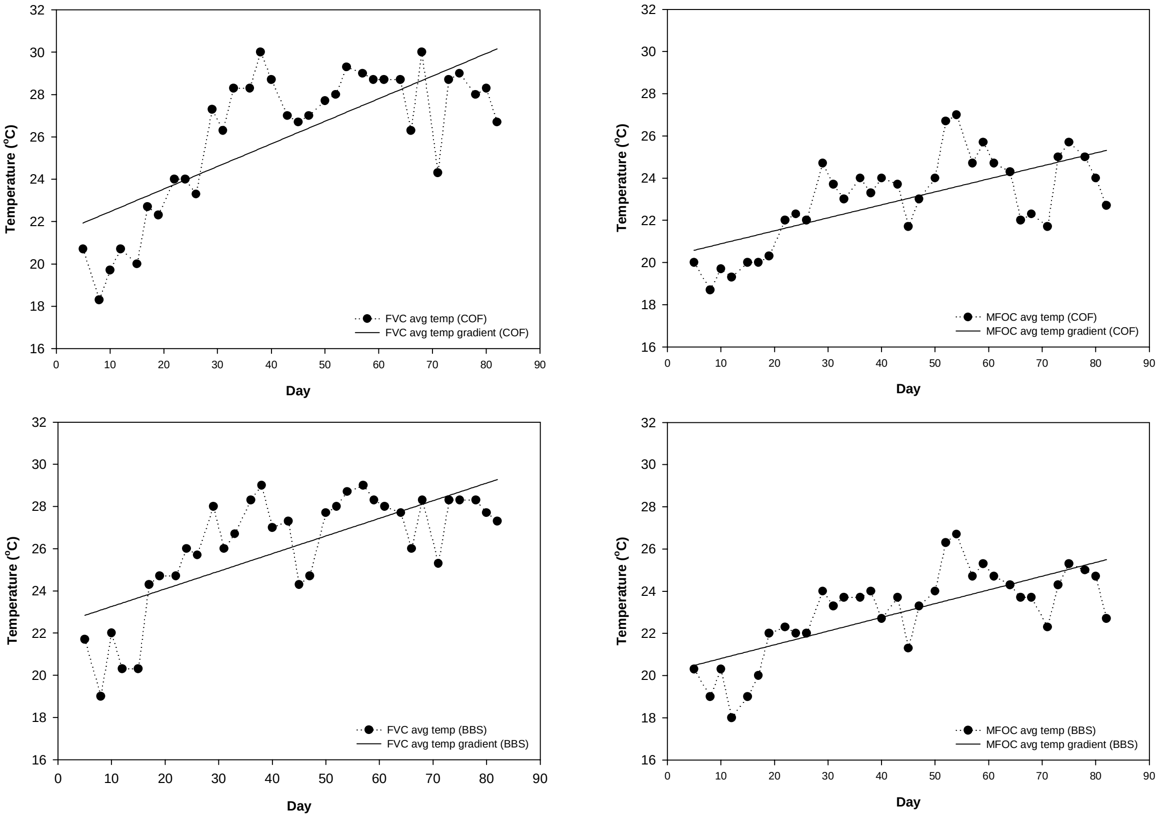


Figure 3.7. Average oxygen concentration gradients for the fruit/vegetable/cardboard (FVC) feedstock and mixed food organics/cardboard (MFOC) feedstock for the centre of the feedstock layer (COF) and 50 mm below the bedding surface (BBS) during the preliminary period (weeks 1-12).

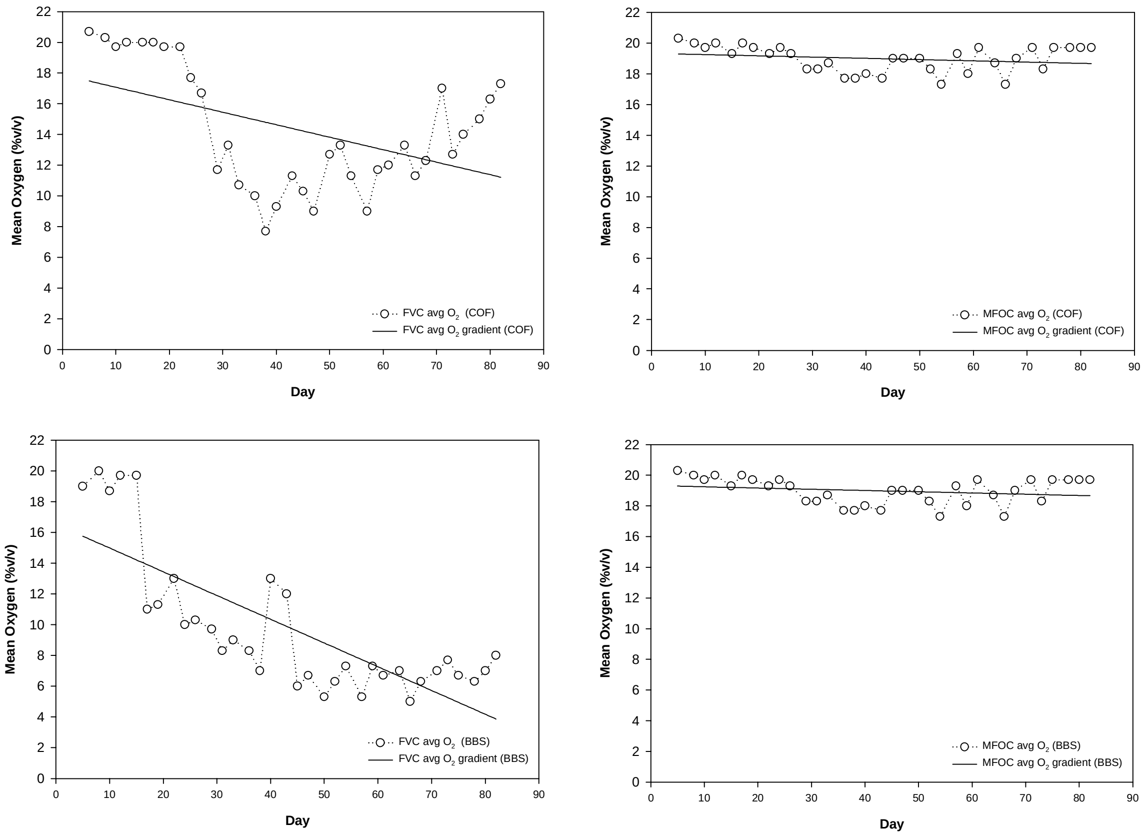


Figure 3.8. Average temperature gradients for the fruit/vegetable/cardboard (FVC) feedstock and mixed food organics/cardboard (MFOC) feedstock for the centre of the feedstock layer (COF) and 50 mm below the bedding surface (BBS) during the final period (weeks 13-24).

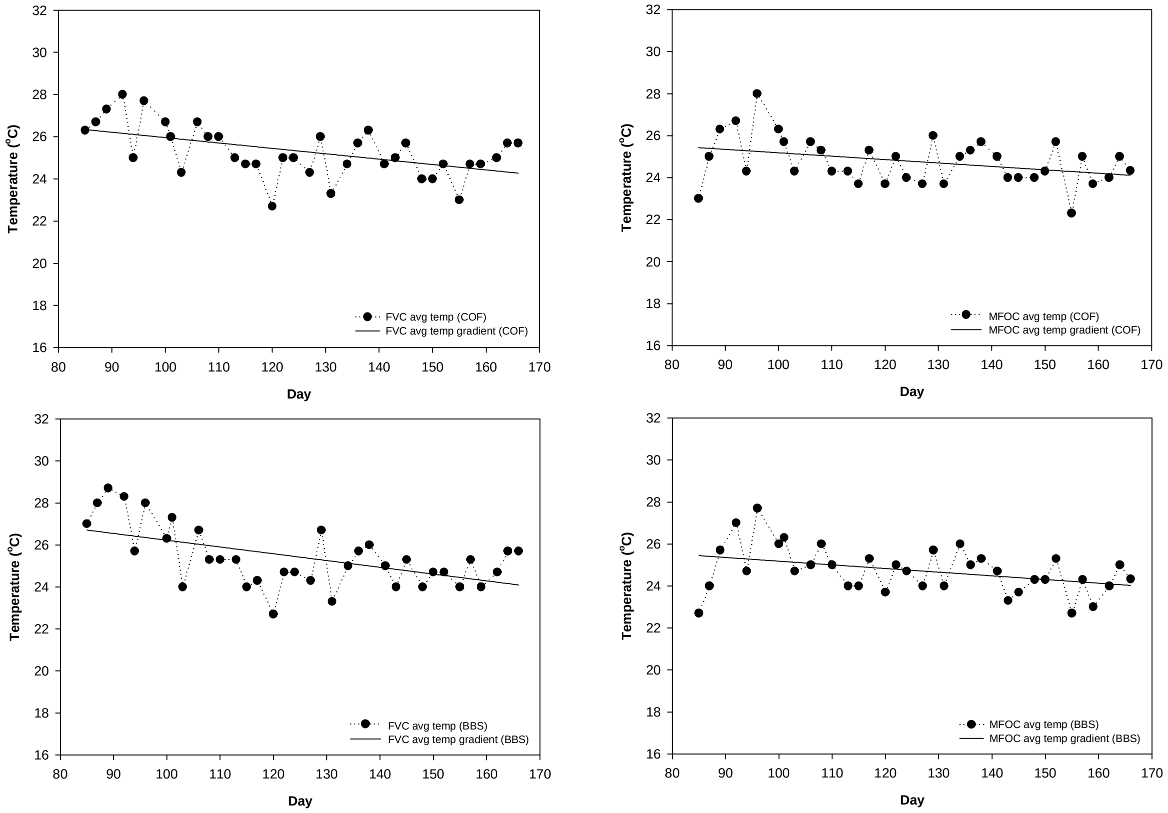


Figure 3.9. Average oxygen concentration gradients for the fruit/vegetable/cardboard (FVC) feedstock and mixed food organics/cardboard (MFOC) feedstock for the centre of the feedstock layer (COF) and 50 mm below the bedding surface (BBS) during the final period (weeks 13-24).

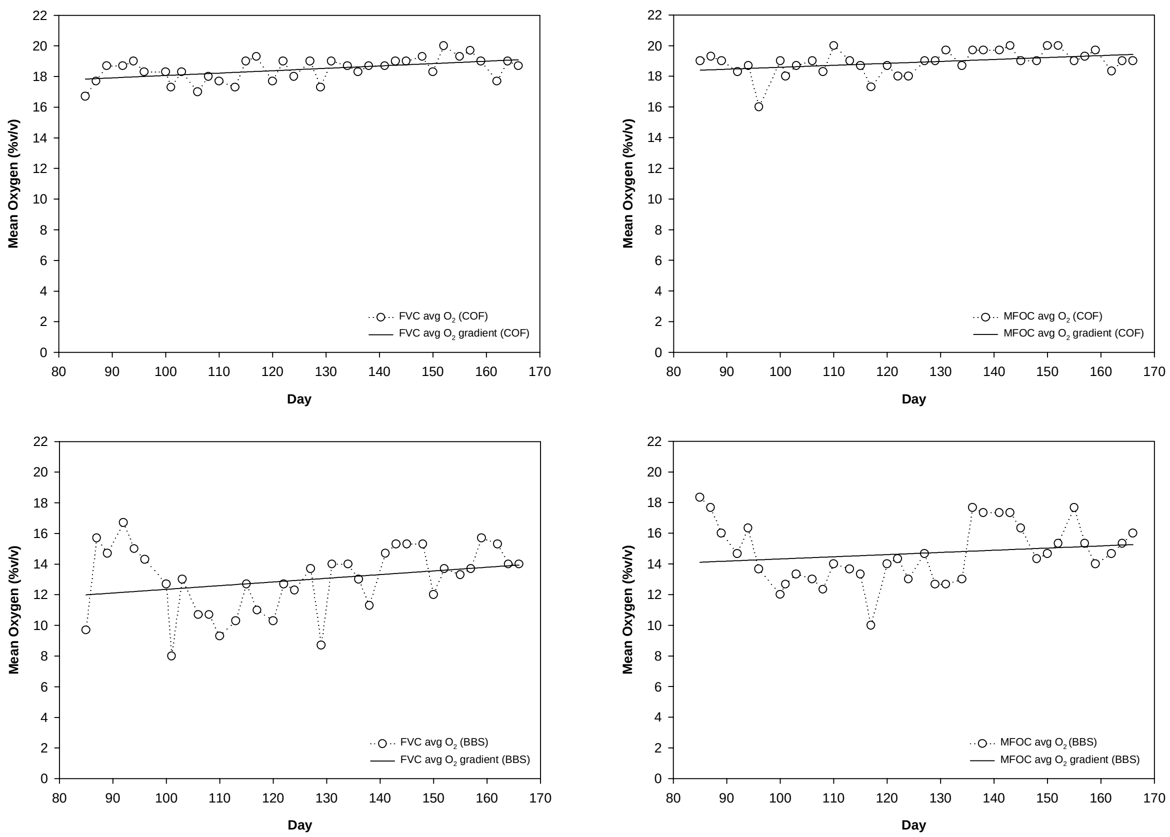


Figure 3.10. Average temperatures for the fruit/vegetable/cardboard (FVC) feedstock and mixed food organics/cardboard (MFOC) feedstock for the centre of the feedstock layer (COF) and 50 mm below the bedding surface (BBS) during the entire trial consisting of 24 weeks.

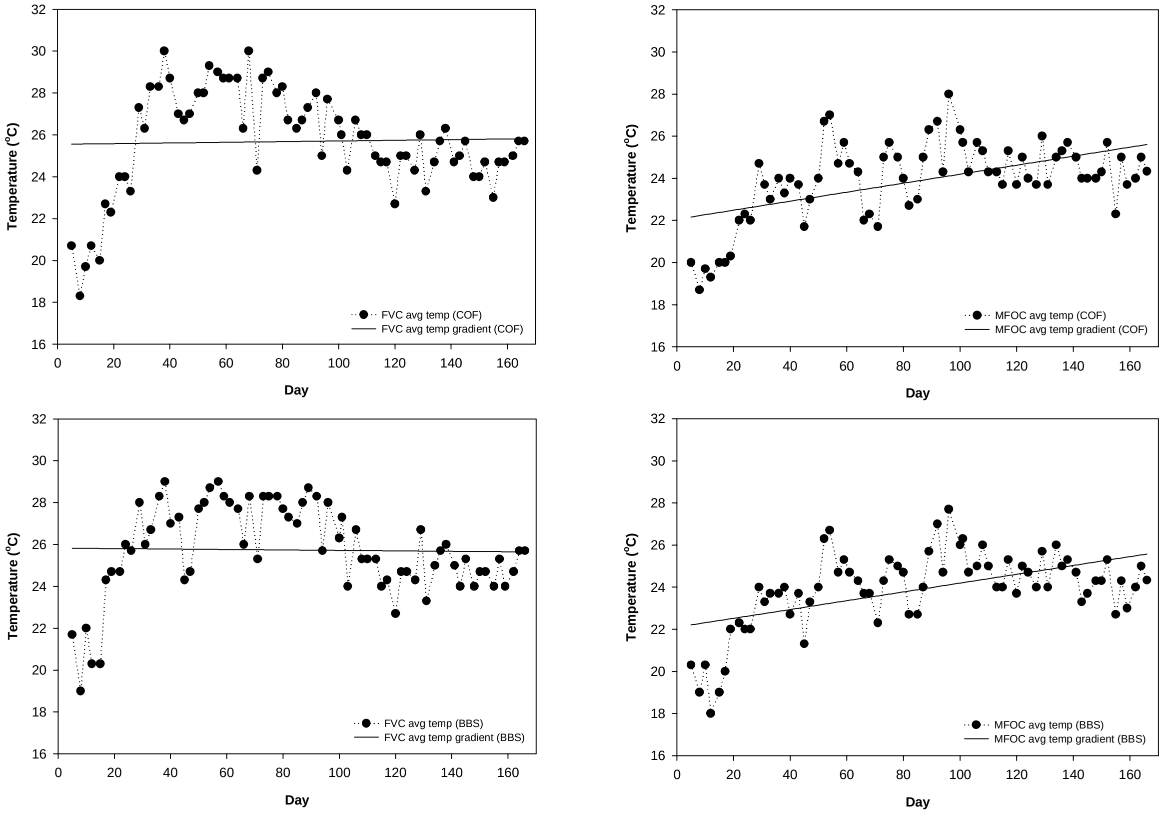
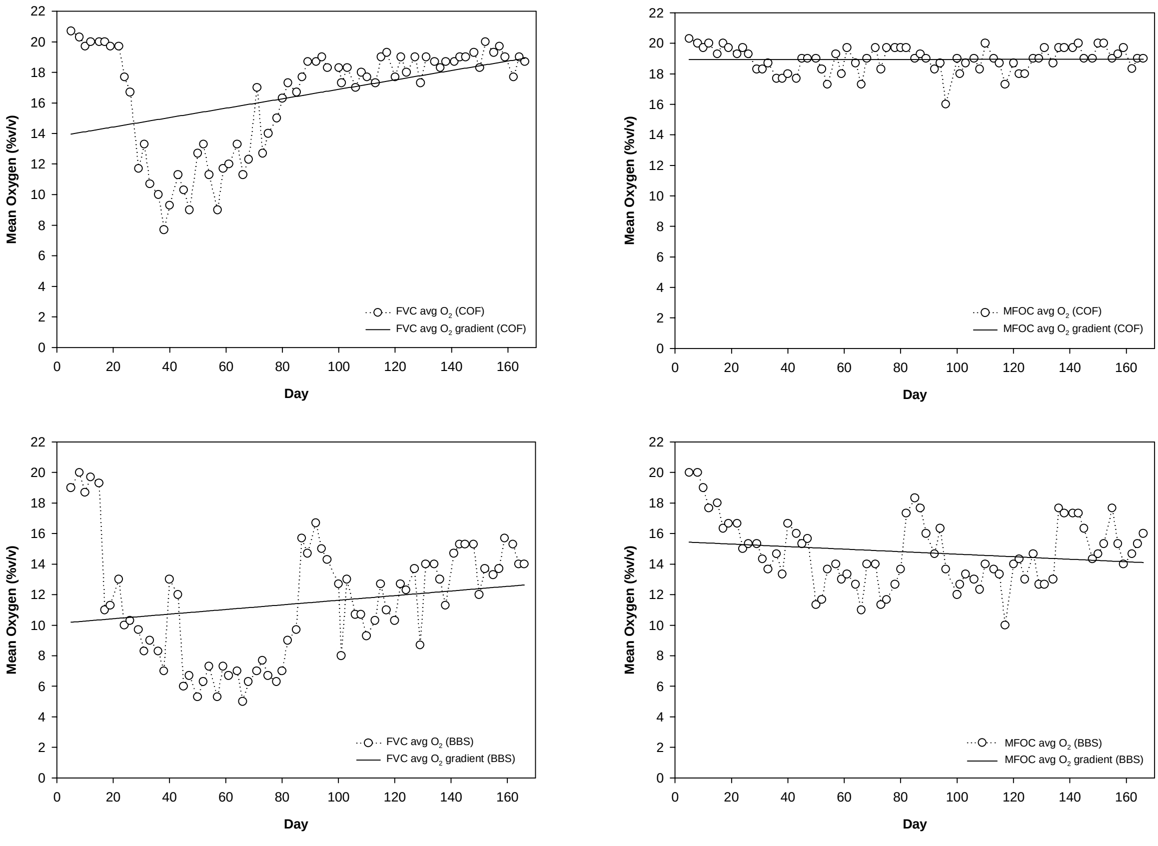


Figure 3.11. Average oxygen concentrations for the fruit/vegetable/cardboard (FVC) feedstock and mixed food organics/cardboard (MFOC) feedstock for the centre of the feedstock layer (COF) and 50 mm below the bedding surface (BBS) for the entire trial consisting of 24 weeks.



2.3.7 Assessment of feedstock recipes

The feedstocks used in this trial were found to be acceptable to the worm population for processing. The feedstock recipes were developed to obtain an ideal moisture content of 70% to 75% and a carbon to nitrogen (C:N) ratio of between 20 and 35:1. Previous studies that have focussed on achieving a feedstock C:N ratio of 20:1 have resulted in high moisture contents that produce excessive amounts of leachate and subsequent moisture problems within the vermiculture units (Recycled Organics Unit, 2000).

This increased focus on feedstock preparation has seemingly resulted in a more suitable feedstock for processing in vermiculture units. The moisture content for the fruit/vegetable/cardboard feedstock, shown in Table 3.2, was reduced to 72.5 %. This is a significant reduction from the moisture content of the raw fruit and vegetable components of 86.6%. The C:N ratio for this feedstock at 69:1 was found to be significantly higher than the anticipated 20-35:1. As previously discussed, this higher C:N ratio may not have been representative of the entire feedstock material due to the large particle size (20 mm) of the cardboard component and the difficulties associated with attaining a representative sample with such large particle sizes. However, it may be interpreted that the amended fruit/vegetable/cardboard feedstock was a suitable recipe for vermiculture processing evident by the moisture content and the acceptability of the feedstock to the worm population. The problems of unprocessed feedstock accumulation, high temperatures and low oxygen within the vermiculture units during the preliminary period were attributed to an excessive loading rate and were solved in the final period by reducing this rate to a more suitable level. The maximum processing capacity for this feedstock was consequently reached and the units were found to operate at a sustainable level under this loading rate of 16.5 kg m^{-2} wk^{-1}.

The maximum processing capacity for fruit/vegetable/cardboard feedstock in this trial (16.5 kg m^{-2} wk^{-1}) was found to be lower than for either of the fruit/cardboard or vegetables/cardboard feedstocks (24.79 and 24.07 kg m^{-2} wk^{-1} respectively) in the previous bench-scale study (Recycled Organics Unit, 2000). These processing capacities, however, are not directly comparable as the current trial tested a mixture of fruit and vegetables with cardboard, to better represent the types of mixed materials produced by generators of these materials in the C&I sector (eg. supermarkets and green grocers). The reduced processing capacity in this trial may have been due to the fact that the feedstock mixture contained an increased percentage of cardboard resulting in a slower rate of decomposition. It is important to note that this was necessary to reduce the volume of leachate produced, and to alleviate the development of anaerobic conditions, which can impact on worm survival.

The mixed food organics/cardboard feedstock had a final moisture content of 72.9% (Table 3.2) after the addition of water. This was due to the dry nature of the bread and meat/poultry components. These components had a moisture content of 32.5% and 55.4% respectively. The addition of water was consequently required to achieve the final suitable moisture content of 72.9%. These ideal feedstock characteristics resulted in acceptance of the feedstock by the worm population and thorough processing within the vermiculture units. This acceptance of the feedstock by the worm population and the minimal accumulation of unprocessed feedstock resulted in an increase in the feedstock loading rate. The worm population successfully processed this increased loading rate of 9.4 kg m^{-2} wk^{-1} and the vermiculture units remained in a healthy and habitable state for the worm stock.

2.3.8 Evaluation of system performance indicators

The system performance indicators, developed in the bench-scale vermiculture trial (Recycled Organics Unit, 2000), and utilised in this trial, allowed a detailed evaluation of the health and performance of the vermiculture units. The hierarchy of system performance indicators: evaluating worm activity, the accumulation of unprocessed feedstock and the monitoring of chemical and environmental data (temperature, oxygen, pH and electrical conductivity), allowed a monitoring schedule to be developed and implemented that resulted in a detailed evaluation of the success of the applied feedstocks and loading rates.

The identification of the sub-optimal performance of the fruit/vegetable/cardboard feedstock at an early stage within the trial prevented system failure and confirmed that the maximum processing capacity for this feedstock had been exceeded. A decrease in the loading rate resulted at the conclusion of the preliminary stage and consequently system performance improved markedly. The worm population, on the other hand, processed the mixed food organics/cardboard feedstock rapidly. As a result, the loading rate was increased by 20% during the preliminary phase of the trial. These revised loading rates were monitored during the final stage of the trial and confirmed as successful.

The performance indicators have consequently been valuable for assessing the health of the vermiculture units and for preventing system failure. The development of these indicators has been crucial for on-site monitoring of vermiculture technology in a commercial environment. If this system of monitoring the health of a vermiculture unit was applied within a C&I sector vermiculture processing environment, it is envisaged that potential health and safety issues, such as odour production and the attraction of pests and vermin, could be prevented.

2.4 Conclusions

This vermiculture trial examined the maximum processing capacities of two feedstocks, a fruit/vegetable/cardboard feedstock and a mixed food organics/cardboard feedstock. These feedstocks were treated in vertical loading, continuous flow vermiculture units inoculated with Tiger worms (*Eisenia* spp.). Laboratory conditions were controlled and the maximum processing capacity was determined by examining the activity of the worms, the accumulation of unprocessed feedstock, and monitoring of chemical and environmental conditions within the vermiculture units.

The initial loading rates, recommended by the bench-scale vermiculture trial (Recycled Organics Unit, 2000) were not found to be the maximum processing capacities for these feedstocks. The fruit/vegetable/cardboard feedstock was recommended as 20.6 kg m^{-2} wk^{-1} (30 L m^{-2} wk^{-1}), however, this was reduced during the course of the trial by 20% to 16.5 kg m^{-2} wk^{-1} (24 L m^{-2} wk^{-1}) due to unit stress. Conversely, the mixed food organics/cardboard feedstock was increased by 20% from a recommended 7.8 kg m^{-2} wk^{-1} (15 L m^{-2} wk^{-1}) to 9.4 kg m^{-2} wk^{-1} (18 L m^{-2} wk^{-1}) due to excellent processing performance.

The extension of the mid-scale vermiculture trial for a further 12 weeks allowed these modified loading rates to be further investigated and to confirm the maximum processing capacities for these feedstocks that can be readily sustained within the context of a C&I sector organisation. These revised loading rates were successfully processed with the vermiculture units reaching approximate steady state conditions. Consistent monitoring and maintenance procedures throughout the trial confirmed the success of these feedstocks for on-site processing by the C&I sector under appropriate management.

The performance indicators used to evaluate the capacity of the vermiculture units to process the feedstocks utilised in this study have been essential in preventing system failure for the fruit/vegetable/cardboard feedstock and for ensuring the maximum processing capacity is reached for the mixed food organics/cardboard feedstock. These system performance indicators are a valuable tool for monitoring vermiculture unit performance in both a domestic and commercial environment.

Section 3: Recommendations

3.1 Skills based training

The outcomes of the vermiculture research program to date should be developed into a skills based training program: "How to install and manage a successful on-site vermiculture organics management system". This program should be delivered to selected Resource NSW, NSW EPA and Local Government staff thereby enabling key staff to deliver the training program throughout New South Wales.

3.2 On-site commercial vermiculture trial

The establishment of an operational on-site vermiculture installation for a C&I sector organisation would provide validation of the results in a real world situation with reduced control over environmental conditions. This project will provide valuable data and case study experience regarding establishment, operation and viability of such an organics management system.

A trial of this nature would provide cost/benefit financial data that could assist in decision making. Such cost/benefit data does not currently exist for use of on-site vermiculture technology in the C&I sector.

3.3 Acclimatisation

The amount of time required for worm stock to adjust to a feedstock has been found to be a critical issue in setting up and managing a successful on-site vermiculture unit. In this trial, and others, it had been found that changes in feedstock composition (eg. manure to food organics) can result in a delay in processing as the worm population adjusts or acclimatises to the new feedstock, which delays the achievement of steady state conditions.

The same situation occurs with changes in the feedstock loading rate, which is of particular relevance to both domestic and C&I sector applications (eg. schools) where a small quantity of initial worm stock is used (due to cost) to initiate an affordable system at a reduced loading rate over time to match increases in worm biomass. An acclimatisation study would provide information on the process of increasing loading rates in a sustainable manner.

3.4 Minimum recommended duration for related vermiculture trials

As a result of this trial, and others, it is recommended that the minimum duration for related vermiculture trials be not less than 6 months. This duration is considered necessary to develop steady state conditions and therefore to deliver meaningful results.

Section 4: Glossary

Please note that terminology used throughout this report is based on standard terminology officially endorsed by the NSW Waste Boards. The glossary shown here contains terms and definitions as reported in the RO Dictionary and Thesaurus (Recycled Organics Unit, 2000b).

Agricultural Organics

Any residual organic materials produced as by-products of agricultural and forestry operations, including: weeds (woody and non-woody); animals (processing residuals, stock mortalities, pests), and crop residuals (woody and non-woody), and manures.

Ammonia (NH_3)

A gaseous compound comprised of nitrogen and hydrogen. Ammonia, which has a (sharp) pungent odour, is commonly formed from organic nitrogen compounds during composting.

Anaerobic

In the absence of oxygen, or not requiring oxygen. Composting systems subject to anaerobic conditions often produce odorous compounds and other metabolites that are partly responsible for the temporary phytotoxic properties of compost. Anaerobic conditions are important for anaerobic digestion systems.

Biosolids

Organic solids or semi-solids produced by municipal sewage treatment processes. Solids become biosolids when they come out of an anaerobic digester or other treatment process and can be beneficially used. Until such solids are suitable for beneficial use they are defined as waste-water solids. The solids content in biosolids should be equal to or greater than 0.5% weight by volume (w/v). Biosolids are commonly co-composted with garden organics and/or residual wood and timber to produce a range of recycled organics products.

Bulking Agent

An ingredient in a mixture of composting raw materials included to improve the structure and porosity of the mix. Bulking agents are usually rigid and dry and often have large particles (for example, straw or wood chips). The terms “bulking agent” and “amendment” are often used interchangeably. See also composting amendment.

Carbon to Nitrogen Ratio (C:N ratio)

The ratio of the weight of organic carbon (C) to that of total nitrogen (N) in an organic material.

Compostable organics

Compostable organics is a generic term for all organic materials that are appropriate for collection and use as feedstocks for composting or in related biological treatment systems (e.g. anaerobic digestion). Compostable organics is defined by its material components: residual food organics; garden organics; wood and timber; biosolids, and agricultural organics.

Electrical Conductivity (EC)

A measure of a solution’s ability to carry an electrical current; varies both with the number and type of ions contained in the solution. Usually measured in deci-Siemens per metre ($dS\ m^{-1}$). See also salinity.

Feedstock

Organic materials used for composting or related biological treatment systems. Different feedstocks have different nutrient concentrations, moisture, structure and contamination levels (physical, chemical and biological).

Food Organics

The Food Organics material definition is defined by its component materials, which include: fruit and vegetable material; meat and poultry; fats and oils; seafood (including shellfish, excluding oyster shells); recalcitrants (large bones >15mm diameter, oyster shell, coconut shells etc.); dairy (solid and liquid); bread, pastries and flours (including rice and corn flours); food soiled paper products (hand towels, butter wrap etc.); and biodegradeables (cutlery, bags, polymers). Such materials may be derived from domestic or commercial and industrial sources. The definition does not include grease trap waste. Food organics is one of the primary components of the compostable organics stream.

Garden organics

The garden organics material definition is defined by its component materials including: putrescible garden organics (grass clippings); non-woody garden organics; woody garden organics; trees and limbs; stumps and rootballs. Such materials may be derived from domestic, commercial and industrial and commercial and demolition sources. Garden organics is one of the primary components of the compostable organics stream.

Leachate

Liquid released by, or water that has percolated through, waste or recovered materials, and that contains dissolved and/or suspended substances and/or solids and/or gases.

Manure

Refers to all faecal and urinary excretion of livestock and poultry that are appropriate for collection and use as feedstock materials for composting or in related biological treatment systems. This material may also contain bedding, spilled feed, water or soil. See also agricultural organics. Such material may be derived from agricultural sources. These materials form one of the material description subcategories within the Agricultural Organics material description.

Moisture Content

The fraction or percentage of a substrate comprised of water. Moisture content equals the weight of the water portion divided by the total weight (water plus dry matter portion).

On-site

A reference to something being done in relation to waste on-site is a reference to that thing being done only on the premises on which the waste was generated.

On-site, Mid-Scale System

A category of on-site composting or vermiculture-based technology with the ability to process between 20 and 250 kg of compostable organics per day. Such systems are usually comprised of an in-vessel processing unit (composting or vermiculture-based) and size reduction equipment (e.g. garden type petrol driven chippers or shredders). Procedures involved in the management of the processing system may involve a combination of manual labour and small mechanical equipment. Mid-scale systems are often used for the treatment of compostable organics produced by the commercial and industrial sector, hospitals and institutions etc.

pH

A measure of the concentration of hydrogen ions in a solution. pH is expressed as a negative exponent. Material that has a pH of 8 has ten times fewer hydrogen ions than a material with a pH of 7. The lower the pH, the more hydrogen ions are present, and the more acidic the material is. The higher the pH, the fewer hydrogen ions present, and the more basic it is. A pH of 7 is considered neutral.

Processing Capacity

The maximum amount (mass or volume) of compostable organics that can be added to a biological treatment system (e.g. composting, anaerobic digestion or vermiculture) per day without causing system failure. System failure is evident when processed organics discharged or obtained from the system are highly anaerobic, odorous or non-stable.

Vermicast

Solid organic material resulting from the transformation in a controlled vermiculture process.

Vermiculture

All vermiculture systems comprise a bedding layer of moist, mature vermicast which provides a medium for worm habitation, and a feeding layer where the raw ingredients are applied, invariably occurring on the upper surface of the bedding. The feeding layer is usually covered with hessian or like protective layer material to minimise moisture loss, excessive temperature gradients and to reduce accessibility to pests and vermin.

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