THE USE OF EARTHWORMS FOR BIOCONVERSION OF SEWAGE SLUDGE AND MUNICIPAL WASTE

A SYNOPSIS OF RELEVANT LITERATURE

Compiled for

ACT DEPARTMENT OF URBAN SERVICES
WASTE MANAGEMENT

by

R. J. Blakemore PhD
c/o CSIRO Division of Entomology
GPO Box 1700
CANBERRA 2601

Ph: (06) 246 4354
Fax: (06) 246 4000

October, 1995

Introduction

The use of earthworms in management of municipal refuse and sewage sludge has been attempted in North America, Europe and Australia. Only a few of the many earthworm species have been trialed for their suitability and efficacy for composting of sewage sludge and municipal wastes. Although there have been many successful results, most schemes have been experimental and there is no currently-available technology-of-choice of which we are aware.

Environmental concerns with "vermicomposting" of sewage sludge and municipal refuse include the fate of heavy metals, major pollutants of sludge. For example, in north America 50-60% of municipal sludges cannot be applied on agricultural land because the cadmium (Cd) content exceeds the permissible heavy metal limit (of 25 ppm) (Tyagi and Couillard, 1991). Different earthworm species deal with heavy metals in different ways: immobilisation and excretion being the most important strategies employed to minimise toxic effects. This implies that the choice of earthworm species depends on the particular task required of it and on the range of products anticipated: protein preparation would best be done using species that egest cadmium, rather than accumulate it. However, this view is an oversimplification and there are a number of important over-riding factors that limit the choice of species.

Other apparent considerations include accumulation and concentration of pesticides such as organochlorines, and the potential for dissemination of pathogens such as enteric bacteria, viruses, parasitic protists (e.g. *Giardia* spp., *Entamoeba* spp. *Cryptosporidium* spp., *Toxoplasma* spp.), nematodes and tapeworms.

The major issues addressed in this synopsis are:

- decomposition of sewage sludge by earthworms
- suitability and efficacy of different species
- accumulation of heavy metals
- accumulation of organic pollutants
- residues of heavy metals and pollutants in castings
- potential for transmission of pathogens
- effect of worm castings on crop yields

Issues not covered are:

- composting technology and economics
- effects of application of sludges to cropping systems on existing earthworm faunas.

Background

Increasing population density, combined with restrictions on ocean dumping, incineration and landfilling require innovative methods of disposal of domestic sewage sludge. Appropriate disposal involves both maximum cost-effective recovery of recycleable constituents and transformation of non-recoverable material into forms which do not present environmental hazards (Applehof, 1981). Two traditional methods of disposal that have received a lot of attention are composting and spreading on the land as fertilizer. Potential problems with either method relate to the persistence of heavy metals and pesticides and to the dissemination of pathogens. These problems have been dealt with in the past by bulking the sludge with innocuous material to dilute concentrations of contaminants and by sterilizing and aerating to reduce pathogens.

Trials on vermicomposting of sewage sludge began in the 1970's (Knight, 1989). Several sewage works in the USA established pilot schemes, amongst the largest were Lufkin, Texas and Keysville, Maryland. The plant at Lufkin could process up to 4 tonnes of sludge a week by spraying thickened sludge over sawdust to create a material suitable for vermiculture using *Eisenia fetida*, the compost worm (Pincince *et al.*, 1981). At Keysville, the method used raised indoor beds and concentrated air-dried sludge. However, the schemes suffered technical difficulties and were uneconomic (Knight, 1989). Attempts at vermicomposting of sludge have suffered the effects of extravagant claims, made often by entrepreneurs or environmental zealots, and lacking in rigorous scientific research.

Scientific investigation of vermicomposting of sludge began in New York in 1976

(Hartenstein and Mitchell, 1978). This work was the basis for a workshop entitled "*Utilization of Soil Organisms in Sludge Management*" (Hartenstein, 1978). Other conference proceeedings include those compiled by Applehof (1981). Review articles appear in Edwards and Neuhauser (1988) while more general reviews on earthworm biology and ecology are by Edwards and Lofty (1977), Satchell (1983) and Lee (1985)[1].

1. Decomposition of sewage sludge by earthworms

Earthworms facilitate the stabilization of organic wastes because their activity maintains aerobic conditions and ingested solids are converted into discrete, odorless casts (Waugh and Mitchell, 1981; Haimi and Huhta, 1987; Loehr *et al*., 1988). Earthworms and microorganisms enhance each other's activity in the composting process (Satchell, 1983a). To be useful in sludge management programs, earthworms must readily colonise sludge, increase the stabilization rate compared with other composting methods, and be economical in terms of operating costs and marketability of final products.

Anaerobically-digested sludge was found to be acutely toxic to *Eisenia fetida* but this toxicity disappeared when the sludge was allowed to age for 2 months as thin layers exposed to air (Hartenstein and Mitchell, 1978). Moreover, the subsequent rate of decomposition was accelerated about 2- to 5-fold following its conversion into casts by earthworms Toxicity was believed to relate to redox potential and it was later shown that anaerobic sludge was non-toxic to *E. fetida* only after it attained an E_h of greater than 250 mV as the sludge aged on soil (Kaplan *et al.,* 1980a). A substrate's redox potential (E_h) is its reducing or oxidising capacity, measured in mV potential difference. High E_h values indicate oxidizing conditions determined by factors such as moisture content, oxygen permeability and organic matter content, factors that perhaps reflect a substrate's habitability for earthworms. However, some sludges that have achieved an E_h of greater than 250 mV may still fail to provide adequate nourishment to earthworms due to retention of toxic but unidentified material (Hartenstein and Mitchell, 1978). Organic wastes containing much ammonia or large amounts of inorganic salts are toxic to *E. fetida* according to Edwards (1988). Hartenstein and Mitchell (1978) reported that *E. fetida*, when placed directly in aerobically-digested sludge drying beds, hasted the decomposition process where the moisture content of the drying sludge was below critical levels. In the absence of earthworms, anaerobic processes predominated over aerobic ones and decompostion slowed. In its untreated state, aerobic sludge assumes a rock-like hardness upon drying and is resistant to rewetting, passage of this sludge through earthworms results in casts which have a large surface area, dry rapidly and yet can readily resorb water. Neuhauser *et al*. (1988) showed that *E. fetida* can double the rate of destruction of volatile solids in aerobically digested sludge after 20 days, probably due to increased aeration and other processes of earthworm activity. These authors also found that optimum *E. fetida* growth was when total sludge solids upper range was about 16% on a wet basis. Experiments by Loehr *et al*. (1988) demonstrated that vermistabilization of fresh aerated sludge with *E. fetida* functioned successfully in trials run for 27 weeks. Conversely, Neuhauser *et al*. (1988) found that as aerobic sludge aged for more that 12 weeks its nutritive value to earthworms decreased rapidly.

No currently operational system involving vermicomposting of municipal sewage sludge is known. Promising early reports from several pilot schemes appear to have been unsustained. Three such schemes are mentioned by Lee (1985). One was a trial in southern California (described by Collier and Livingstone, 1981) that was discontinued despite producing vermicompost favourable for plant growth and acceptable to growers. Another operation established at Lufkin, Texas (Pincince *et al*., 1981) failed when the earthworms died in a particularly hot summer. A third system in Ontario (Canada) used industrial sludges to produce vermicompost which was applied to soils at a rate that was estimated (by Bird and Hale, 1982) to raise the concentration of heavy metals in the soil above the legally prescribed limits within 45 years.

The potential of earthworms to enhance the decomposition of sludge, though intensively investigated, has not been fully realised. Biodegradation of biosolids by composting appears to be a more acceptable option (Miller, 1991). It is possible that earthworms may yet play a role if it could be demonstrated that their maintenance did not add expense or complexity to standard composting techniques.

[1]References that are books or conference prceedings are not provided with this report, but selected chapters or sections have been copied and are attached.

2. Suitability and efficacy of different species

The most common earthworm used for vermicomposting is *Eisenia fetida* although many other species have potential and may be suitable. Advantages of *E. fetida* are that it growth rapidly, feeds on almost any organic matter, it has a wide temperature tolerance, can be easily handled, has a high reproductive rate and has more known about its biology than any other species (Hartenstein, 1983; Edwards and Bater, 1992).

Several authors have compared species: Neuhauser *et al*. (1988) studied all five, and Edwards (1988) four, of the following species: *Eisenia fetida*, *Eudrilus eugeniae*, *Perionyx excavatus*, *Eisenia veneta* and *Amynthas corticis*. Edwards and Bater (1992) and Reinecke *et al*. (1992) made comparisons between the first three in this list. In general, *Eisenia fetida* was found to be superior to the other species in terms of its wide temperature tolerance, high reproductive rate and efficiency in converting organic wastes. *Eudrilus eugeniae* and *Perionyx excavatus* were also effective but their narrow temperature tolerances limits them to more tropical situations. The fecundity of *Eudrilus eugeniae* is lower than that of *E. fetida* but studies by Graff (1982) showed *E. eugeniae* had its highest reproduction when fed on sewage sludge. A summary of findings from these and several other reports is given in Table 1.

Optimal environmental conditions for the growth and reproduction of *Eisenia fetida* fed on aerobic wastes are a temperature range of 15-25°C, moisture content of 43-90% and pH of 5-9 (Kaplan *et al*. 1980a; Edwards, 1988; Neuhauser *et al.*, 1988; Edwards and Bater, 1992; Reinecke *et al*., 1992). *Eudrilus eugeniae* has narrower optimum temperatures in the range 20-29°C (Neuhauser *et al.*, 1988, Neuhauser *et al.*, 1979) while for *Perionyx excavatus* optimum temperatures are 15-30°C (Neuhauser *et al.*, 1988). Results of a study by Reinecke *et al*. (1992) confirmed that *Eisenia fetida* had a wider tolerance for temperatures than either *E. eugeniae* or *P. excavatus*. Although temperature tolerances depend somewhat on the acclimation of earthworms, temperatures of 30°C were found to be detrimental to the growth of five species by Neuhauser *et al*. (1988) and 35°C was fatal. Nevertheless, it may be possible to utilise heat generated by the composting processes to enable heat-tolerant species to survive in cooler climates.

Little is known of the environmental requirements and vermicomposting capabilities of *Eisenia andrei*, a species occasionally found with *E. fetida* in cultures (see Table 1).

In theory, maintaining a mixture of several species (a polyculture) could accomplish greater sludge stabilization that cultures of a single species due to variable partitioning of resources and environmental tolerances. However, in experiments it was not obvious that polyculture had any advantages in sludge stabilisation compared to single cultures of *Eisenia fetida* or *Eudrilus eugeniae* (Neuhauser *et al*., 1988) and in mixed cultures *E. fetida* often becomes dominant (Edwards and Bater, 1992).

Other organisms have interactions with earthworms in composting processes including nematodes, enchytraeids (pot worms), isopods (slaters), collembolans (springtails), mites and the fly and beetle larvae as well as microbes and fungi. It is possible that different earthworm species will have different associations with these various composting organisms.

Table 1. Species of earthworms with potential for bioconversion of sludge.
Note, most recent nomenclatural changes give these names:
Amynthas diffringens = Amynthas corticis
Amynthas hawayana = Amynthas gracilis
Eisenia foetida = Eisenia fetida
Dendrobaena veneta = Eisenia veneta

Species (common name)	**Temperature ranges**	**Usefulness**	**References**
Amynthas gracilis	20-28°C optimum	Not suitable	Kaplan *et al.* (1980b); Neuhauser *et al.* (1988)
Amynthas rodericensis	20-28°C optimum	Not suitable	Kaplan *et al.* (1980b)

Eisenia andrei (red tiger worm)*	Unknown	Characteristics similar to *E. fetida* but is less common.	Haimi and Huhta (1978); Sheppard (1988); van Gestel *et al.* (1992)
Eisenia fetida (tiger worm)*	0-35°C tolerated; 20-25°C optimum.	Effective and most widely used.	Watanabe and Tsukamoto (1976); Tsukamoto and Watanabe (1977); Kaplan *et al.* (1980a); Graff (1982); Hartenstein (1983); Reinecke and Venter, 1985; Venter and Reinecke, 1987; Neuhauser *et al.* (1988); Edwards, 1988; Edwards and Bater, 1992.
Eisenia veneta	3-33°C tolerated; 15-25°C optimum	Efficient at converting sludge but has a low reproductive rate.	Neuhauser *et al.* (1988); Edwards and Bater, 1992.
Eudrilus eugeniae (African night-crawler)	9-30°C restriction; 20-28°C optimum	Effective, but has narrow temperature requirements.	Neuhauser *et al.* (1979); Graff (1982); Neuhauser *et al.* (1988); Edwards, 1988; Edwards and Bater, 1992.
Lumbricus rubellus (red worm)*	13-22°C optimum	Not well researched	Pincince *et al*. (1981)
Perionyx excavatus (Indian blue worm)	9-30°C restriction; 15-30°C optimum	Prolific and effective but has restricted temperature range.	Kale *et al.* (1982); Neuhauser *et al.* (1988); Edwards, 1988; Edwards and Bater, 1992; Reinecke and Reinecke, 1994.

* *Eisenia andrei*, *E. fetida* and *Lumbricus rubellus* may have been confused in earlier literature and are all called "red worms" by some worm growers.

3. Accumulation of heavy metals

Note: µg/g or mg/kg are synonymous with parts per million (ppm).

The term heavy metals is taken to include several elements which have a biological function or are toxic to some organisms. The most important environmental pollutants, listed in Lee (1985), are lead (Pb), cadmium (Cd), mercury (Hg), zinc (Zn), copper (Cu), nickel (Ni), antimony (Sb) and bismuth (Bi). Many other elements are involved but most attention has been given to the first two in the list. Because earthworms ingest large quantities of substrate they are particularly susceptible to accumulation of pollutants which may be passed to other animals directly (eg. by predation by birds or mammals), or indirectly via plant uptake of earthworm products from the soil. The main issues are toxicity and the rate and means of heavy metal accumulation in earthworms.

Hartenstein and Mitchell (1978) reported that various sludge treatments with salts of heavy metal at these concentrations were not toxic to *E. fetida* over a six week period: Cd at 100 ppm, Hg at 100 ppm, Cr at 3000 ppm, Ni at 1000 ppm, Pb at 5000 ppm. The same sludge treated with Cu at 2500 ppm or with Zn at 10000 ppm was toxic. Of the foregoing metals, only Cd accumulated in the tissues of *E. fetida* and the authors concluded that this accumulation of Cd only occurs after it has been liberated from sludge by forces such as microbial metabolism. Toxicity studies by Hartenstein *et al.* (1980) found that *E. fetida* fed for 4 weeks on sludge doubled their biomass despite the presence of heavy metals, although long-term sublethal effects may reduce their fertility (Ireland, 1983). Yet when removed from exposure to sublethal concentrations of heavy metals *E. fetida* was capable of compensatory growth (Neuhauser *et al*., 1984).

Toxicity of five heavy metals to *E. fetida* were tested by Malecki *et al.* (1982), minimum concentrations (in ppm dry weight) that retarded growth were: 50 for Cd; 100 for Cu; 12,000 for Pb, 200 for Ni and 2,000 for Zn. Minimum concentrations for suppression of reproduction (again in ppm) were: 25 for Cd, 100 for Cu, 4,000 for Pb, 200 for Ni and 500 for Zn. The results of their short-term (8 weeks) and long-term (20 weeks) studies showed that Cd was the most toxic in terms of earthworm growth and reproduction. However, their results differed depending on which chemical compound of a heavy metal was fed to the earthworm, especially insoluble forms were less toxic (see also Neuhauser *et al*, 1984). This last finding may explain why conflicting data sometimes appears in the literature on concentrations that have deleterious effects on earthworms.

Numerous authors, as reviewed by Beyer (1981) and Ireland (1983), have reported that earthworms can accumulate heavy metals from both contaminated and non-contaminated environments. Storage ratios or concentrations factors (these two terms are interchangeable and refer to the ratio of a metal in tissue to that in the substrate) tend to be highest in infertile soil and lowest in media high in organic matter, such as sewage sludge. Ireland (1983) states that Cd does not appear to concentrate in earthworm tissues indefinitely and the ratio decreases with increasing Cd concentration, unlike Pb which appears to accumulate continuously. Carter *et al*. (1983) found some regulation of Zn and Cu, but not of Cd which reached a maximum in earthworm tissue of about 34 ppm (cf. 100 ppm recorded by Helmke *et al*. (1979) and 400 ppm found by Mori and Kurihara (1979)). Beyer (1981) calculated the storage ratios for 29 heavy metals from the data of Helmke *et al*. (1979), the only positive values were for Zn, Se, Br Au, Hg and Cd, this latter storage ratio being 28:1.

Graff (1982) examined the accumulation of heavy metals in *Eisenia fetida* and *Eudrilus eugeniae* before and after feeding on compost made from municipal garbage. The heavy metal contents (in µg/g dry weight) before and after feeding were: for *E. fetida*, Cu 4 to 29, Zn 140 to 640, Pb 3 to 14, Cd 2 to 9, Hg 0.1 to 14; for *Eudrilus eugeniae*: Cu 17 to 55, Zn 165 to 360, Pb 10 to 72, Cd 4 to 6, Hg 1 to 15. These data indicate that the earthworms are extracting the heavy metals from the compost and are concentrating them their tissues. Except for Cu and Pb, all these final concentrations exceed the minimum EPA accepted thresholds for heavy metals in biosolid products (Anon. 1994).

Heavy metal concentrations for *Aporrectodea caliginosa*, a common pasture worm, in soils treated for 10 yrs with municipal waste compost were reported by Ma (1982). The concentration factors in earthworm tissue were ca. 10-140 times for Cd, 2-75 times for Zn, and 0.2-2.6 times for Pb, only sometimes was Cu concentrated while Ni, Fe, Mn and Cr were not concentrated. Similar studies were made by Andersen (1979) and Tomlin *et al*. (1992). Lee (1985) states that the data of Ma (1982) cannot be assumed to apply for other species of earthworms nor for different soils as the physico-chemical state of the soil determines the solubility of the heavy metals added.

Mechanisms of adsorption and excretion of Pb by earthworms are not clearly understood. Although Pb was absorbed by *Eisenia fetida* in investigations conducted by Wielgus-Serafinska and Kawka (1976), as reviewed in Lee (1985), increasing concentrations of Pb in the soil did not result in similar increased concentrations in the earthworm tissues. These workers concluded that increasing environmental concentrations of Pb stimulate excretory mechanisms in *E. fetida*, perhaps through excretion with mucus from the body wall. This is a possible explanation as Fleming and Richards (1982) demonstrated surface adsorption of heavy metals on the mucus coating of *Eisenia fetida*.

The pathways of heavy metal accumulation and excretion vary between species. Earthworms that tolerate high concentrations of toxic heavy metals either do not absorb the metal, accumulate it in a non-toxic form or excrete it efficiently (Ireland and Richards, 1979; Ireland, 1983). Andersen and Laursen (1982) studied the excretion and distribution of 5 heavy metals in 3 species of earthworm. They found the metals to be handled in at least three ways in *L. terrestris*:

(a) immobilization in fatty (chloragogen) cells of the gut wall
(b) storage in waste nodules (or "brown bodies") formed within the body cavity
(c) excretion through the calciferous glands.

The metals Pb, and Cd were accumulated in the gut wall and from here transferred to waste nodules in *L. terrestris* whereas Mn, Zn and Fe were regulated, mainly through excretion via the calciferous glands. Although fed on different contaminated soils, the total Pb content of *Aporrectodea longa*, which has relatively poor calciferous glands, was 6 µg/g compared with 24 µg/g for *L. terrestris* yet the Pb concentration in waste nodules were 89 ppm and 57 ppm, respectively. This was taken to indicated that a species with poorly developed calciferous glands excretes less Pb. Andersen and Laursen (1982) also found that Cd, which was accumulated by all three earthworm species, was concentrated in *L. terrestris*, *Aporrectodea rosea* and *A. longa* in chloragogen cells (by very effective binding in Cd-metallothioneins) and, only in the latter species, in waste nodules too. The main implication of these different pathways is that Pb and Cd when taken up and stored may be released only when the earthworm dies.

4. Accumulation of organic pollutants

Toxicity and accumulation of various biocides in earthworms, as for heavy metals, is of concern; in particular the fate of pesticide residues and polychlorinated biphenyls (PCBs). Several authors have investigated earthworm tissue concentrations of organochlorines (eg. Edwards and Thompson, 1973; Haimi *et al*., 1992), but few data are available for PCBs (eg. Kreis *et al*., 1987).

Pesticide residues in sludge are unlikely to exceed concentrations that are quoted in the literature as being toxic to earthworms, however some can accumulate. Organochlorines are particularly problematical because they are persistent in the environment, are relatively harmless to earthworms and are lipophilic so may be concentrated in earthworm fatty tissues (Lee, 1985). Other pesticides are apparently not accumulated by earthworms and, although organophospates and carbamates may be more toxic, these compounds are generally less persistent in the evironment.

There is little quantitative information available on the accumulation and transfer of pesticides in earthworms feeding on sludge. However, it is apparent that the concentration and decay rates differ depending upon the species and substrates. *Eisenia fetida* was found to be the most tolerant (except to the carbamate, aldicarb) of several species tested for sensitivity to a range of biocides (Stenersen, 1979 as reported in Lee, 1985).

In soils, organochlorines are also the most important contaminants with regards transfer of pesticides along food chains via bird and mammal predators of earthworms (eg Brown, 1978, Edwards and Lofty, 1977; Lee, 1985). For example, Beyer and Gish (1980) sprayed dieldrin, haptachlor and DDT onto soil plots and measured concentrations in earthworms; average ratios compared to soil were: dieldrin, 8; heptachlor epoxide, 10 and DDT, 5.

5. Residues of heavy metals and pollutants in casts

Few studies have considered the fate of heavy metals in vermicomposts as opposed to studies of earthworm casts from contaminated soils (eg. Morgan and Morgan, 1992). Ireland (1983) stated that total Cd in earthworm casts from contaminated soils was sometimes higher than in the surrounding soils for some species, whereas concentration ratios of Zn, Pb and Cu in casts were more variable. In contrast, Hartenstein *at al*. (1980) reported that passage of sludge through the gut of *E. fetida* did not increase Cd, nor Cu, Ni, Pb and Zn. Carter *et al*. (1983) found that in *L. rubellus*, the Cd levels in casts tended to increase as contaminated sludge concentration increased up to a certain level but that Cu and Zn levels showed no relationship with sludge concentrations.

In response to initial observations by Hartenstein and Mitchell (1978), Kaplan *et al*. (1980c) investigated self toxicity and interspecific toxicity of casts of *E. fetida*. They found that casts produced when feeding on soil were self-toxic and cross-toxic to *Eudrilus eugeniae* and to two *Amynthas* spp but this toxicity disappeared after casts were aged 2 weeks. However, the casts produced by *E. fetida* and *Eudrilus eugeniae* when fed on activated sludge were self-toxic but not cross-toxic. Aging for 6 weeks made these casts more highly toxic both to themselves and one another except where the casts had been amended with soil. The cause of this toxicity was attributed to microbial populations within the casts and it was recommended that soil and fresh sludge be added when making vermicompost to ensure the earthworms were not exposed to high concentrations of their own casts.

6. Potential for transmission of pathogens

Earthworms feeding on sludge may be potential vectors of a wide range of parasitic and pathogenic organisms (Lee, 1985; Satchell, 1983a). Activated sludge does not generally support growth to human enterics but anaerobic sludge does (Taber, 1976). It has been determined that passage of organic material through the gut of an earthworm can reduce numbers of some micororganisms and increase numbers of others (Satchell, 1983a). Spores and cysts of some parasites pass unharmed through the gut of earthworms while some pathogens are reduced.

Brown and Mitchell (1981) reported that *Eisenia fetida* feeding on a growing medium inoculated with *Salmonella eneritidus*, reduced populations of this enteric pathogen by 42 times, compared to controls, after 28 days with the greatest rate of reduction of pathogen in the first 4 days. Satchell (1983a) reports the findings of two researchers (Day, 1950 and Brusewitz, 1959) that two species of Enterobacteriaceae, *Serratia marcessens* and *Escherichia coli* inoculated in soil were killed when ingested by the earthworm *Lumbricus terrestris*.

Eggs of some nematode parasites of mammals and birds, eg. *Ascaris lumbricoides*, *A. suum* and *Ascarida galli*, are not destroyed following passage through the earthworm *Lumbricus terrestris* (Rysavy, 1969; Hartenstein and Mitchell, 1978). Associations between nematodes and earthworms were reviewed by Poinar (1978) who listed some 150 associations only some of which are parasitic to other than earthworms. Edwards and Lofty (1977) summarised the range of helminth parasites for which earthworms are intermediate hosts. Which, if any, of these parasites are of concern in the ACT is unknown but it is unlikely that a region with high levels of public hygiene and medicine would be greatly at risk.

Microbial pathogens are perhaps the greatest concern, yet the NSW EPA code (Anon., 1994) specifically targets only faecal coliform and salmonellae and makes no mention of other enterobacteria nor viruses. The code of practice for reduction of pathogens in biosolids products for "Unrestricted Use" set out by NSW EPA (Anon., 1994) tentatively approves three processes: composting, heating and drying and pH and heating. In addition the composted product is subjected to a minimum pathogen regrowth potential assay system as approved by the EPA. The three processes, respectively, require a compost to reach 53°C for 5 days or 55°C for 3 days; heating to 70°C for 1 hr and drying to 75% solids; raising the alkalinity to pH 12 with heating to 52°C and drying to >50% solid. Such regimes would invariably be fatal for earthworms unless they were free to migrate to areas where temperatures were abated. Survival of the earthworms would be advantageous for colonization of fresh substrates, but may be undesirable if they acted as agents for transmission of pathogens or pollutants. The proposed EPA requirements for stabilisation of biosolid products for "Restricted Use" are less stringent (Anon., 1994).

7. Effect of worm castings on crop yields

Worm casts from an organically rich source medium are sometimes referred to as "vermicompost". Despite claims by some producers, there is little scientific literature on the subject of the usefulness of vermicompost on plant growth (Edwards and Burrows, 1988).

During passage through the gut of the earthworm ingested material is mixed, and has its physical, chemical and biotic components altered, but very little material is actually digested by the worm and the structure and composition of the casts is dependent on the composition of the food source (Edwards and Burrows, 1988; Buchanan *et al*., 1988). Organic materials differ greatly in their nutrient content; processing by the earthworm can change the form of these compounds but has very little effect on the total amounts contained. The physical structure of the casts also depends on the source material, however the final product usually comprises finely mixed and relatively stable aggregates with good structure, porosity, and moisture-holding capacity (Edwards, 1981; Lee, 1985). The composition of casts from earthworms feeding on sewage sludge can be expected to have a different composition to those produced by earthworms feeding on unamended soils.

Casts produced from soil have increased nitrate and exchangeable calcium, magnesium, potassium and phosphorus than the original soil (Lunt and Jacobson, 1944). Other chemical and physical changes in earthworm casts compared to parent soil are given by Zhang and Schrader (1993) and changes in microbial populations are covered by Satchell (1983).

Edwards and Burrows (1988) also compared the nutrient contents of several organic wastes before and after being worked by earthworms: all had increased nitrate, soluble P and exchangeable potassium, calcium and magnesium when worm-worked. These authors found that emergence and growth of a range of seedlings in pots was frequently enhanced in these worm-worked compared to unworked media. Fresh earthworm casts may contain high salt soluble concentrations, especially of Na^+, sufficient to damage plants. Stark *et al.* (1978) found that leaching cast with water reduced these salts to tolerable levels while still retaining most of the plant beneficial nutrients.

Some physico-chemical changes imposed on sludge in conversion to vermicompost are given by Hartenstein and Hartenstein (1981). Chemical analyses by Buchanan *et al*. (1988) of vermicompost from a municipal sewage sludge had 48 ppm N-nitrate, 11 ppm available P, 2442 ppm available K, 4354 ppm available Ca and 1858 available Mg. These values were comparable to a commercial compost mix although the composition of the source sludge were not given.

Haimi and Huhta (1987) made comparisons between the physical, chemical and biotic nature of worm-worked and "wormless" sewage sludge and between vermicompost and conventional compost. Whereas the wormless sludge remained as a compact clump, the worms produced a mass of castings. Physicochemical analyses revealed only minor differences between worm-worked and other products and these authors concluded that vermicompost was superior to ordinary compost only with regard to its physical structure.

Handreck (1986) compared the porosities, salinities, nutrient contents, pH values and trace elements of several vermicomposts and potting mixes. Vermicomposts varied widely in total nutrient content: most had negligible amounts of soluble N-nitrates but had ample amounts of P and some had high concentrations of Zn and Cu. Plant (*Matthiola incana*) growth in potting mixes reflected the nutrient status of the vermicomposts: in general plants were N deficient (requiring a supplementary supply) and some were further affected by toxic levels of trace elements although there was adequate P (and often K and S) and trace elements.

A glasshouse trial by Springett and Syers (1979) in New Zealand grew ryegrass seedlings for 8 days in soil in pots with or without added phosphorous (P) fertilizer and with or without casts of *Aporrectodea caliginosa* or *Lumbricus rubellus*, the soil and casts they collected from the same pasture site. Their results showed a consistent increase in plant growth in the presence of earthworm casts, in addition that obtained from added fertilizer, of between 5% to 50% in root length and 5% to 49% in shoot length relative to growth in the soils without casts.

In Germany, Graff and Makeschin (1980) grew ryegrass in soil in pots which had either contained and then had removed after 11 days specimens of *L. terrestris*, *A. caliginosa* and *E. fetida* or had held no earthworms. The grass was harvested three times and total plant yields were compared. Dry matter and root production were significantly higher in the worm-worked soils, for each species, than in the control soils. The increased yields, relative to the controls for *L. terrestris*, *A. caliginosa* and *E. fetida* were: for shoot dry matter, 100%, 68% and 52%, respectively and for total root production, 59%, 38% and 24%, respectively. It is assumed that some contribution to these increased yields is attributable to the presence of casts but that earthworm burrows and exudates also had an influence.

As reported by Lee (1985), Collier (1978) planted sunflower, tomatoes and corn in three treatments: (a) *E. fetida* casts derived from sewage sludge, (b) in unprocessed sludge that was ground to a similar size to the casts and (c) in untreated soil. All plants in (b) treatment died within 2 month whereas they thrived in the other two treatments and plants in treatment (a), i.e., those in *E. fetida* casts, yielded 4 times those in (c). In contrast, Frederickson and Knight (1988) found that tomatoes grown in sludge worked by *E. fetida* showed a reduced rate of development after 109 days compared to tomatoes grown in a commercial compost. This they attributed to a high pH and excess nutrients in the worm-worked material.

Few reports deal with field trials involving the application of vermicompost. Kale *at a*l. (1992) studied vermicompost in a rice paddy in India. Significant increases in the colonisation of soil by microbes (including N-fixers, Actinomycetes, spore formers and Mycorrhizae) occurred in the experimental plots compared to the control plots without added vermicompost. Higher levels of total N in the experimental plot where vermicompost was added was attributed to higher counts of N-fixing microbes. Lee (1985) mentions findings by Khan (1966) that the growth of maize on a loamy soil in Pakistan was enhanced by the addition of casts of *Metaphire posthuma* and that their effect was greater than was obtained with the addition of farmyard manure. In India, Reddy (1988) compared the growth of an ornamental shrub, *Vinca rosea* and rice, *Oryza sativa*, in soils with or without the casts of *Pheretima alexandri*. Those *V. rosea* plants in casts grew better and produced flowers and fruits earlier than plants in soil alone. Rice growing for 4 months in pots with highest concentrations of added casts grew best, the whole plant lengths (means) being 81.5 cm in soil mixed with casts compared to 62.8 cm in soil alone.

Conclusions

Early experiments that demonstrated the potential benefits of sludge vermicomposting for increasing rates of stabilization and for production of useful products have not been realized. Various pilot trials and schemes were initiated to put theory into practice, none of which have succeeded. Reasons for failure have varied but perhaps the single underlying cause was failure to maintain suitable conditions for earthworm survival. These conditions include regulation of suitable food supplies, temperatures, moisture levels, aeration, and contaminants.

Vermicomposting relies almost entirely on one earthworm, *Eisenia fetida*, a generalist species able to tolerate wide variations in environmental conditions compared to other species. Only a small fraction of the several thousand species of earthworms there are in the world have been studied with regards their vermicomposting potential, those that have appear to have very different behaviours and requirements. Regardless of these differences, unless a species has better handling properties than *Eisenia fetida* then it is unlikely to be commercially exploited.

Assuming the sludge environment could be maintained with sufficient precision then there remains problems of heavy metal contamination, pesticides and pathogens. The importance for each of these depends very much on the composition of the sludge. Levels of toxins and pathogens require monitoring, both before and after processing. Heavy metals are perhaps of greatest concern, and it may be possible to exploit some aspect of earthworm behaviour for their removal. Processing by the earthworms may alter the solubility or stability of some heavy metals, or perhaps enhance other physical, chemical or microbial means of removal (eg. Tyagi and Couillard, 1991). Accumulation of pesticide may be less of a problem as these chemicals and their metabolites often have known rates and products of decay. Earthworms may be used in combination with conventional composting techniques to reduce pathogens, although the temperatures involved are incompatible for earthworm survival.

Vermicomposting of municipal wastes may be particularly suitable option for production of useable products. Composition and consistency of these products would largely depend on the composition of the initial waste materials and of any materials with which they are combined. As for sludge treatment, there would be a requirement to constantly monitor nutrients, contaminants and to prevent pathogen regrowth, in both the raw materials and the final products.

References

Note: a copy of Hartenstein, R (1978). *Utilization of Soil Organisms in Sludge Management*. Natl. Tech. Inf. Services, PB286932, was unobtainable by the time this paper was compiled. References to papers in Hartenstein, 1978 are therefore taken from secondary sources.

Anon. (1994). Interim code of practice for use and disposal of biosolids products. Draft - June, 1994. Environment Protection Authority of New South Wales.

Andersen, C. 1979. Cadmium, lead and calcium content, number and biomass, in earthworms (Lumbricidae) from sewage sludge treated soil. Pedobiologia, 19: 309-319.

Andersen, C. and Laursen, J. 1982. Distribution of heavy metals in *Lumbricus terrestris*, *Aporrectodea longa* and *A. rosea* measured by atomic absorbtion and X-ray fluorescence spectrometry. Pedobiologia, 24: 347-356.

Applehof, M. (compiler), 1981. *Workshop on the Role of Earthworms in the Stabilization of Organic Residues.* Volume 1, Proceedings. Beech Leaf Press. Kalamazoo, Michigan. pp 315.

Beyer, W.N. 1981. Metals and Terrestrial Earthworms (Annelida: Oligochaeta). In: Applehof, M. (compiler), 1981. *Workshop on the Role of Earthworms in the Stabilization of Organic Residues.* Volume 1, Proceedings. Beech Leaf Press. Kalamazoo, Michigan. pp 135-150.

Beyer, W.N. and Gish, C.D. 1980. Persistence in earthworms and potential hazards to birds of soil applied DDT, dieldrin and heptachlor. J. Appl. Ecol., 17: 295-307.

Bird, S.J.G. and Hale, I.M. 1982. Development of vermicomposting operations at a prototype plant. Consultants' report to A.E. Burgess, Waste Control Divsion, Environment Canada, Ottawa, Ontario. 175 pp.

Brown, A.W.A.1978. *Ecology of Pesticides*. John Wiley and SOns, New York.

Brown, B.A. and Mitchell, M.J. 1981. Role of the earthworm, *Eisenia foetida*, in affecting the survival of *Salmonella enteritidis* ser. *typhimurium*. Pedobiologia 22: 434-438.

Bruzewitz, G. (1959). Studies on the influence of earthworms on numbers of species and role of micro-organisms in soils. Arch. Mikrobiol. 33: 52-82 [In german].

Buchanan, M.A., Russell, G. and Block, S.D. 1988. Chemical characterization and nitrogen mineralization potentials of vermicompost derived from differing organic wastes. In: Edwards, C.A. and Neuhauser, E.F. (eds), 1988. *Earthworms in Waste and Environmental Management*. SPB Academic Publishing bv, The Hague. pp 231-239.

Carter, G.S., Kenney, E.A., Guthrie, T.F., and Timmenga, H. 1983. Heavy metals in earthworms in non-contaminated and contaminated agricultural soil from near Vancouver, Canada. In: Satchell, J.E. (ed.) *Earthworm Ecology*. Chapman and Hall, London. pp. 267-274.

Collier, J. 1978. Use of earthworms in sludge lagoons. In: R. Hartenstein (ed) *Utilization of Soil Organisms in Sludge Management*. Natl. Tech. Inf. Services, PB286932. Springfield, Virginia, pp 131-133.

Collier, J. and Livingstone, D. 1981. Conversion of municipal wastewater treatment plant residual sludges into earthworm castings for use as a fertile topsoil. Report to U.S. National Science Foundation, Appropriate Technology Program. Grant No. ENV77-16832 A01.

Day, G.M. (1950). Influence of earthworms on soil micro-organisms. Soil Science 69: 175-184.

Edwards, C.A. 1981. Earthworms, Soil Fertility and Plant Growth. In: Applehof, M. (compiler), 1981. *Workshop on the Role of Earthworms in the Stabilization of Organic Residues.* Volume 1, Proceedings. Beech Leaf Press. Kalamazoo, Michigan. pp 61-85.

Edwards, C.A. 1988. Breakdown of animal, vegetable and industrial organic wastes by earthworms. In: Edwards, C.A. and Neuhauser, E.F. (eds), 1988. *Earthworms in Waste and Environmental Management*. SPB Academic Publishing bv, The Hague. pp 21-31.

Edwards, C.A. and Bater, J.E. 1992. The use of earthworms in environmental management. Soil Biol. Bichem. 24: 1683-1689.

Edwards C.A. and Burrows, I. 1988. The potential of earthworm compost as plant growth media. In: Edwards, C.A. and Neuhauser, E.F. (eds), 1988. *Earthworms in Waste and Environmental Management*. SPB Academic Publishing bv, The Hague. pp 211-220.

Edwards, C.A. and Lofty, J.R. 1977. *Biology of Earthworms*. Second edition. Chapman and Hall, London.

Edwards, C.A. and Neuhauser, E.F. (eds), 1988. *Earthworms in Waste and Environmental Management*. SPB Academic Publishing bv, The Hague. pp 392

Edwards, C.A. and Thompson, A.R. 1973. Pesticides and the soil fauna. Residue Rev. 45: 1-79.

Fleming, T.P. and Richards, K.S. 1982. Localization of adsorbed heavy metals on the earthworm body surface and their retrieval by chelation. Pedobiologia, 23: 415-418.

Fosgate, O.T. and Babb, M.R. 1972. Biodegradation of animal waste by *Lumbricus terrestris*. J. Dairy Sci., 55: 870-872.

Frederickson, J. and Knight, D. 1988. The use of anaerobically digested cattle solids for vermiculture. In: Edwards, C.A. and Neuhauser, E.F. (eds), 1988. *Earthworms in Waste and Environmental Management*. SPB Academic Publishing bv, The Hague. pp 33-47.

Gestel, C.A.M. van, Dirven-van Breemen, E.M. and Baerselman, R. 1992. Influence of environmental conditions on the growth and reproduction of the earthworm *Eisenia andrei* in an artificial soil substrate. Pedobiologia 36: 109-120.

Graff, O. 1982. Vergleich der Regenswurmaten *Eisenia foetida* und *Eudrilus eugeniae* hinsichlich ihrer Eignung zur Proteinwinnung aus Abfallstoffen. Pedobiologia 23: 277-282. [In german, english summary].

Graff, O and Makeschin, F. (1980). Crop yield of rye-grass influenced by the excretions of three earthworm species. Pedobiologia 20: 176-180. [In german, english summary].

Haimi, J. and Huhta, V. 1987. Comparison of composts produced from identical wastes by "vermistabilization" and conventional composting. Pedobiologia 30: 137-144.

Haimi, J., Salminin, J., Huhta, V., Knuutinen, J. and Palm, H. 1992. Bioaccumulation of organochlorine compounds in eathworms. Soil Biol. Biochem. 24: 1699-1703.

Handrek, K.A. 1986. Vermicomposts as components of potting media. Biocycle. 10/86: 58-62.

Hartenstein, R. (ed), 1978. *Utilization of Soil Organisms in Sludge Management*. Conference Proceedings. U.S. Department of Commerce, National Technical Information Services, PB286932. Springfield, Virginia. pp 171.

Hartenstein, R. 1983. Assimilation by the earthworm *Eisenia fetida*. In: Satchell, J.E. (ed). 1983. *Earthworm Ecology: from Darwin to Vermiculture.* Chapman and Hall, London, pp 297-308.

Hartenstein, R. and Hartenstein, F. 1981. Physicochemical changes effected in activated sludge by the earthworm *Eisenia fetida*. J. Environ. Qual. 10: 377-382.

Hartenstein, R. and Mitchell, M.J. 1978. *Utilization of Earthworms and Microorganisms in Stabilization, Decontamination and Detoxification of Residual Sludges from Treatment of Wastewater, Final Report.* U.S. Department of Commerce, National Technical Information Services, PB 286018, Springfield, Virginia, 34 pp.

Hartenstein, R., Neuhauser, E. F. and Collier, J. 1980. Accumulation of heavy metals in the earthworm *Eisenia foetida*. J. Env. Qual. 9: 23-26.

Helmke, P.A., Robarge, W.P., Korotev, R.L. and Schomberg, P.J. 1979. Effects of soil-applied sewage sludge on concentrations of elements in earthworms. J. Environ. Qual., 8: 322-327.

Honeycutt, M.E., Roberts, B.L. and Roane, D.S. 1995. Cadmium disposition in the earthworm *Eisenia fetida*. Ecotoxicology and Environmental Safety 30 (2): 143-150.

Ireland, M.P. 1983. Heavy metal uptake and tissue distribution in earthworms. In: Satchell, J.E. (ed). *Earthworm Ecology: from Darwin to Vermiculture.* Chapman and Hall, London, pp. 247-265.

Ireland, M.P. and Richards, K.S. 1979. The occurrence and localisation of heavy metals and glycogen in the earthworms *Lumbricus rubellus* and *Dendrobaena rubida* from a heavy metal site. Histochemistry, 51: 153-166.

Kale, R.D., Bano, K. and Krishnamoorthy, R.V. 1982. Potential of *Perionyx excavatus* for utilizing organic wastes. Pedobiologia, 23: 419-425.

Kaplan, D., Hartenstein, R., Neuhauser, E.F. and Malecki, M.R. 1980a. Physicochemical requirements in the environment of the earthworm *Eisenia foetida*. Soil Biol. Biochem., 12: 165-171.

Kaplan, D., Hartenstein, R., Neuhauser, E.F. and Malecki, M.R. 1980b. Role of the pheretimoid worms *Amynthas hawayana* and *A. rodericensis* in soils and recycling. Rev. Ecol. Biol. Sol., 17: 347-352.

Kaplan, D., Hartenstein, R. and Neuhauser, E.F. 1980c. Coprophagic relations among the earthworms *Eisenia foetida, Eudrilus eugeniae* and *Amynthas* spp. Pedobiologia 20: 74-84.

Khan, A.W. 1966. Earthworms of West Pakistan and their utility in soil improvement. Agic. Pak. 17: 192-197.

Knight, D. (1989). Nice work for a worm. New Scientist. 8 July: 31-35.

Kreis, B., Edwards, G., Guendet, G. and Tarrabellas, J. 1987. The dynamics of PCBs between earthworm populations and agricultural soils. Pedobiologia 30: 379-388.

Lee, K.E. 1985. *Earthworms. Their Ecology and Relationships with Soils and Land Use*. Academic Press, Sydney. pp 411.

Lee, K.E. 1992. Some trends and opportunities in earthworm research or: Darwin's children - the future of our discipline. Soil Biol. Biochem. 24(12): 1765-1771.

Loehr, R.C., Martin, J.H. and Neuhauser, E.F. 1988. Stabilization of liquid municipal sludge using earthworms. In: Edwards, C.A. and Neuhauser, E.F. (eds), 1988. *Earthworms in Waste and Environmental Management*. SPB Academic Publishing bv, The Hague. pp 95-110.

Lunt, H.A. and Jacobson, H.G.M. 1944. The chemical compostion of earthworm casts. Soil Science, 58: 367-375.

Ma, Wei-Chun. 1982. The influence of soil properties and worm-related factors on the concentration of heavy metals in earthworms. Pedobiologia 24: 109-119.

Malecki, M.R., Neuhauser, E.F. and Loehr, R.C. 1982. The effect of metals on the growth and reproduction of *Eisenia foetida* (Oligochaeta, Lumbricidae). Pedobiologia 24: 129-137.

Miller, F.C. (1991). Biodegradation of solid wastes by composting. In: Martin, A.M. (ed). 1991. *Biological Degradation of Wastes*. Elsevier Science Publishers, London. pp 1-31.

Mitchell, M.J., Hornor, S.G. and Abrams, B.I. 1980. Decomposition of sewage sludge in drying beds and the potential role of the earthworm *Eisenia foetida*. J. Environ. Qual., 9: 373-378.

Mitchell, M.J., Mulligan, R.M., Hartenstein, R. and Neuhauser, E.F. 1977. Conversion of sludges into "topsoils" by earthworms. Compost Science. 18(4): 28-32.

Morgan, J.E. and Morgan, A.J. 1992. Heavy metal concentrations in the tissues, ingesta and faeces of ecophysiologically different earthworm species. Soil Biol. Biochem. 24: 1691-1697.

Mori, T. and Kurihara, Y. (1979). Accumulation of heavy metals in earthworms (*Eisenia fetida*) grown in composted sewage sludge. Sci. Rep. Tohoku Univ., Ser. IV (Biol.) 37: 289-297.

Neuhauser, F., Kaplan, D.L. and Hartenstein, R. 1979. Life history of the earthworm *Eudrilus eugeniae*. Rev. Ecol. Biol. Sol., 16: 525-534.

Neuhauser, E.F., Loehr, R.C. and Malecki, M.R. 1988. The potential of earthworms for managing sewage sludge. In: Edwards, C.A. and Neuhauser, E.F. (eds), 1988. *Earthworms in Waste and Environmental Management*. SPB Academic Publishing bv, The Hague. pp 9-20.

Neuhauser, E.F., Malecki, M.R. and Loehr, R.C. 1984. Growth and reproduction of the earthworm *Eisenia fetida* after exposure to sublethal concentrations of metals. Pedobiologia 27: 89-97.

Pincince, A.B., Donovan, J.F. and Bates, J.E. 1981. Vermicomposting of municipal solid wastes and municipal wastewater sludges. In: Applehof, M. (compiler), 1981. *Workshop on the Role of Earthworms in the Stabilization of Organic Residues.* Volume 1, Proceedings. Beech Leaf Press. Kalamazoo, Michigan. pp 207-219.

Poinar, G.O. 1978. Associations between nematodes (Nematoda) and Olicochaetes (Annelida). Proc Helminth. Soc. Washingon 45: 202-210.

Reddy, M.V. 1988. The effect of casts of *Pheretima alexandri* (Beddard) on the growth of *Vinca rosea*, and *Oryza sativa* L. In: Edwards, C.A. and Neuhauser, E.F. (eds), 1988. *Earthworms in Waste and Environmental Management*. SPB Academic Publishing bv, The Hague. pp 241-248.

Reinecke, A.J. and Reinecke, S.A. 1994. Influence of worm density on growth and cocoon production of the asiatic earthworm *Perionyx excavatus* (Oligochaeta, Megascolecidae). Eur. J. Soil Biol., 30 (1): 29-33.

Reinecke, A.J. and Venter, J.M. (1985). The influence of moisture on the growth and reproduction of the compost worm *Eisenia fetida* (Oligochaeta). Rev. Ecol. Biol. Sol., 22: 473-481.

Reinecke, A.J., Viljoen, S.A. and Saayman, R.J. 1992. The suitability of *Eudrilus eugeniae*, *Perionyx excavatus* and *Eisenia fetida* (Oligochaeta) for vermicomposting in Southern Africa in terms of their temperature requirements. Soil Biol. Biochem. 24: 1295-1307.

Rysavy, B. 1969. Lumbricidae - an important parasitological factor in helminthoses of domestic and wild animals. Pedobiologia. 9: 171-174.

Sabine, J.R. 1983. Earthworms as a source of food and drugs. In: Satchell, J.E. (ed). 1983. *Earthworm Ecology: from Darwin to Vermiculture.* Chapman and Hall, London, pp.285-296.

Satchell, J.E. (ed). 1983. *Earthworm Ecology: from Darwin to Vermiculture.* Chapman and Hall, London,

Satchell, J.E. 1983a. Earthworm microbiology. In: Satchell, J.E. (ed). *Earthworm Ecology: from Darwin to Vermiculture.* Chapman and Hall, London. pp 351-365.

Sheppard, P.S. 1988. Specific differences in cocoon and hatchling production in *Eisenia fetida* and *Eisenia andrei*. In: Edwards, C.A. and Neuhauser, E.F. (eds), 1988. *Earthworms in Waste and Environmental Management*. SPB Academic Publishing bv, The Hague. pp 83-92.

Springett, J.A. and Syers, J.K. 1979. The effect of earthworm casts on ryegrass seedlings. In: T.K. Crosby and R.P. Pottinger (eds). Proceedings 2nd Australasian Conference on Grassland Invertebrate Ecology. pp 44-47. Government Printer, Wellington.

Stark, N., Pawlowski, P. and Bodmer, S. 1978. Quality of earthworm castings and the use of compost on arid soils. In: R. Hartenstein (ed) *Utilization of Soil Organisms in Sludge Management*. Natl. Tach. Inf. Services, PB286932. Springfield, Virginia, pp 87-102.

Stenersen, J. 1979. Action of pesticides on eathworms. Part I. The toxicity of chollinesterase-inhibiting insecticides to earthworms as evaluated by laboratory tests. Pestic. Sci. 10: 66-74.

Suzuki, K.T., Yamamura, M. and Mori, T. (1980). Cadmium-binding proteins induced in the earthworm. Arch. Environ. Contam. Toxicol. 9: 415-424.

Taber, W.A. 1976. Wastewater microbiology. Annu. Rev. Microbiol. 30: 263-277.

Tomlin, A.D., Protz, R., Martin, R.R., McCabe, D.C. and Lagace, R.J. 1992. Relationships amongst organic matter content, heavy metal concentrations, earthworm activity, and soil microfabric on a sewage sludge disposal site. Geoderma, 57: 89-103.

Tsukamoto, J and Watanabe, H. 1977 Influence of temperature on hatching and growth of *Eisenia foetida*. Pedobiologia 17: 338-342.

Tyagi, R.D. and Couillard, D. (1991). An innovative biological process for heavy metals removal from municipal sludge. In: Martin, A.M. (ed). 1991. *Biological Degradation of Wastes*. Elsevier Science Publishers, London. pp 307-321.

Venter, J.M. and Reinecke, A.J. 1987. Can the commercial earthworm Ei*senia fetida* (Oligochaeta) reproduce parthenogenetically or by self fertilization? Rev. Ecol. Biol. Sol., 24: 157-170.

Watanabe, H. and Tsukamoto, J. 1976. Seasonal changes in size class and stage structure of lumbricid

Eisenia foetida population in a field compost and its practical application as the decomposer of organic waste matter. Rev. Ecol. Biol. Sol., 13: 141-146.

Waugh, J.H. and Mitchell, M.J. 1981. Effect of the earthworm, *Eisenia foetida*, on sulfur speciation and decompositon in sewage sludge. Pedobilogia 22: 268-275.

Wielgus-Serafinska, E. and Kawka, E. 1976. Accumulation and localization of lead in *Eisenia foetida* (Oligochaeta) tissues. Folia Histochem. Cytochem., 14: 315-320.

Zhang, H. and Schrader, S. Earthworm effects on selected physical and chemical properties of soil aggregates. Biol. Fertil. Soils. 15: 229-234.