17. Vermicomposting organic wastes: A review

Jorge Domínguez[1] and Clive A. Edwards[2]

[1]Departamento de Ecoloxía e Bioloxía Animal, Universidade de Vigo, E-36200 Spain
[2]Soil Ecology Laboratory, Ohio State University, Columbus, Ohio 43210 USA

SUMMARY

The importance of biological processes in the management of organic wastes has been widely recognized and this Chapter deals with one of the most efficient methods for converting solid organic materials into environmentally-friendly useful and valuable products. Vermicomposting is an accelerated process of bio-oxidation and stabilization of organic wastes involving interactions between earthworms and microorganisms.

Earthworms, the main characters of this process, are described briefly, showing how these animals can be important organic waste decomposers and converters. The different earthworm species that are suitable for vermicomposting have quite different requirements for their optimal development, growth and productivity in organic wastes and we review the life cycles of these species and the general requirements of ideal vermicomposting earthworm species. Vermicomposting is a complex biological and ecological process and to illustrate some of the important physical, chemical and biological transformations occurring during it, we present a case study.

Although earthworms are critical for the process, in vermicomposting, complex interactions between the organic matter, microorganisms, earthworms and other soil invertebrates result in the fragmentation, bio-oxidation and stabilization of organic matter. The vermicomposting system sustains complex food webs, and at the same time, modifies different chemical forms of several nutrient elements into inorganic compounds readily available to plants, which are important for nutrient dynamics.

Soil Zoology for Sustainable Development in the 21st Century
S.H. Shakir Hanna and W.Z.A. Mikhaïl, eds, Cairo 2004

Keywords: earthworms, vermicomposting, organic wastes, bio-oxidation, bio-stabilization, composting

WHAT IS VERMICOMPOSTING?

In recent years, the disposal of organic wastes from domestic, agricultural and industrial sources has caused increasing environmental and economic problems and many different technologies to address this problem have been developed. The growth of earthworms in organic wastes has been termed vermiculture and the processing of organic wastes by earthworms is known as vermicomposting. Vermicomposting, which involves the composting of organic wastes through earthworm activity, has proven to be successful in processing sewage sludge and solids from wastewater (Neuhauser *et al.* 1988, Domínguez *et al.* 2000), materials from breweries (Butt 1993), paper waste (Butt 1993, and Elvira *et al.* 1995), urban residues, food and animal wastes (Edwards *et al.* 1985, Allevi *et al.* 1987, Edwards 1988, Elvira *et al.* 1996 a, Dominguez and Edwards 1996), as well as horticultural residues from processed potatoes, dead plants and the mushroom industry (Edwards 1988).

Vermicomposting is a decomposition process involving the joint action of earthworms and microorganisms. Although microorganisms are responsible for the biochemical degradation of organic matter, earthworms are crucial drivers of the process, by fragmenting and conditioning the substrate and dramatically altering its biological activity. Earthworms act as mechanical blenders and by comminuting the organic matter they modify its physical and chemical status, gradually reducing its C:N ratio, increasing the surface area exposed to micro-organisms and making it much more favourable for microbial activity and further decomposition. Greatly during passage through the earthworm gut, they move fragments and bacteria-rich excrements, thus homogenizing the organic material.

The end product, or vermicompost, is a finely divided peat-like material with high porosity and water holding capacity that contains most nutrients in forms that are readily taken up by the plants. These earthworm casts are rich in organic matter and have high rates of mineralization that implicates a greatly enhanced plant availability of nutrients, particularly ammonium and nitrates.

EARTHWORMS

Earthworms are defined as segmented worms, bilaterally symmetrical, with an external gland (clitellum) producing an egg case (cocoon), a sensory lobe in front of the mouth (prostomium), with the anus at the posterior end of the animal body, no limbs but possessing a small number of bristles (chaetae) on each segment. They are hermaphrodites and reproduction normally occurs through copulation and cross-fertilization, following which each of the mated individuals can produce cocoons (oothecae) containing between one and twenty fertilized ova. The resistant cocoons, which can survive many years, are tiny and roughly lemon-shaped. After an incubation period that varies according to species and climatic conditions, the cocoons hatch. The young earthworms, which are white and only a few millimeters in length after emerging from the cocoons, gain their specific adult pigmentation within a day. Assuming favourable conditions, many species can reach sexual maturity within weeks after emergence, although species that live in soil take longer. Mature individuals can be distinguished easily by the presence of the clitellum, which is a pale- or dark-coloured swollen band, located behind the genital pores. The clitellum secretes the fibrous cocoon, and the clitellar gland cells produce a nutritive albuminous fluid which fills the cocoon. Earthworms can continue to grow in size after completing their sexual development, but never add segments.

The number of earthworm species is enormous; according to Reynolds (1994), there are as many as 7,254 species in the Oligochaeta, of which about half (3,627) are terrestrial earthworms, with an average annual addition of 68 new species. The most common earthworms, which originated in Europe, have migrated to North America, western Asia as well as many other parts of the world, belong to the family Lumbricidae. In West Africa, many of the common earthworms belong to the family Eudrilidae and in South Africa to the Microchaetidae. In Australia and other parts of Asia, the Megascolecidae are most common, and Glossoscolecidae predominate in Central and South America (Reynolds 1998). For most species the original genus and species description is the only information available and usually little or nothing is known of their life cycles, distribution, ecology, etc.

Through feeding, burrowing and casting, earthworms modify the physical, chemical and biological properties of organic matter and soil. Physical properties affected by earthworms include aggregation, stability and porosity, while soil biological and chemical properties that are modified include nutrient cycling (mainly N and P), organic matter decomposition rates, and chemical forms of nutrients in soil and their availability to plants. They also change pH and organic matter dynamics, in terms of quality and quantity, microbial and invertebrate activity (including production of enzymes and plant growth regulators), and the abundance, biomass, species composition and diversity of the microflora and fauna (Lavelle *et al.* 1998).

Different species of earthworms have quite different life histories and styles, occupying different ecological niches and these have been formally classified into three major ecological categories, based primarily on their feeding and burrowing strategies (Bouché 1977):

Epigaeic species are essentially litter dwellers; they live in organic horizons, in or near the surface litter and feed primarily on coarse particulate organic matter, ingesting large amounts of undecomposed litter. These species produce ephemeral burrows into the mineral soil for periods of diapause, so their activities and effects are limited primarily to the upper few centimetres of the soil-litter interface. They are essentially "litter transformers". They are typically small in body size, uniformly-pigmented species with high metabolic and reproductive rates which represent adaptations to the highly variable environmental conditions at the soil surface. In habitable tropical regions, earthworms of this category can be found above-ground, in microbially rich accumulations of soil and water in the axils of plants such as Bromeliaceae (Lavelle and Barois 1984). When the environmental conditions within heterotrophic decomposition systems are unsuitable or food is limited, epigaeic species are difficult to find, despite their great potential for rapid reproduction.

Species in this group include *Lumbricus rubellus, Eisenia fetida, Eisenia andrei, Dendrobàena rubida, Eudrilus eugeniae, Perionyx excavatus* and *Eiseniella tetraedra.*

Endogaeic earthworm species live deeper in the soil profile and feed primarily on both soil and associated organic matter. They have little pigmentation and they generally construct horizontal, deep branching burrow systems which are filled with cast material as they move through the organic-mineral layer of the soil. Earthworms of this type can burrow deep and unlike r-selected epigaeic earthworms, they are k-selected species (Satchell, 1980, and Lavelle 1983) that require a long time to achieve their maximum weight and appear to be more tolerant of starvation than epigaeic species (Lakhani and Satchell 1970). These species are apparently of no major importance in litter incorporation and decomposition since they feed on subsurface material and are important in other soil formation processes, including root decomposition, soil mixing, and aeration. Species such as *Allolobophora caliginosa, A. Rosea* and *Octolasion cyaneum* are included in this group.

Anecic earthworm species live in more or less permanent vertical burrow systems which may extend several meters into the soil profile. The permanent burrows of anecic earthworms create a microclimatic gradient, and the earthworms can be found either shallow or deep in their burrows depending on the prevailing soil conditions. They cast at the soil surface and emerge at night to feed primarily on surface litter, manure and other partially decomposed organic matter which they pull down into their burrows. Some anecic species may also create heaps of cast material termed "middens" at the burrow entrance, consisting of a mixture of cast, soil and partially-incorporated surface litter. Characteristically, these earthworms are large in size as adults and anteriorly and dorsally dark brown in colour. Their reproduction rates, evidenced from cocoon production, are relatively low. Anecic earthworms, intermediate on the r-k scale (Satchell 1980, and Lavelle 1983), are very important agents in organic matter decomposition, nutrient cycling, and soil formation, accelerating the pedological processes in soils worldwide. *Lumbricus terrestris*, *Aporrectodea trapezoides* and *Allolobophora longa* are included in this ecological group.

The barriers between these ecological categories are not always easy to draw and some species cannot be neatly assigned into one or the other category; for example, in agricultural soils, earthworms generally burrow deeper than they do in more compacted grassland and forest soils. Additionally, the categories can be sub-divided. The endogaeic group, for example, can be split into "epi-endogaeic" and "hypo-endogaeic" depending on whether the species in question selects the upper or the lower parts of the organo-mineral horizon.

EARTHWORM SPECIES SUITABLE FOR VERMICOMPOSTING

Looking at this general ecological classification it is obvious that only epigaeic species can be expected to be suitable for vermiculture and vermicomposting. Moreover, to consider a species to be suitable for use in vermicomposting they should possess certain specific biological and ecological characteristics: *i.e.*, an ability for colonizing organic wastes naturally; high rates of organic matter consumption, digestion and assimilation of organic matter; be able to tolerate a wide range of environmental factors; have high reproductive rates, by producing large numbers of cocoons that should not have a long hatching time, and their growth and maturation rates from hatchlings to adult individuals should be rapid; they should be strong, resistant and survive handling. Not too many species of earthworms have all these characteristics.

Temperate species

Eisenia fetida (Savigny, 1826) **and *Eisenia andrei*** Bouché, 1972

These closely-related species are those most commonly used for management of organic wastes by vermicomposting and there are several reasons why these two species are preferred: (1) they are peregrine and ubiquitous with a world-wide distribution and many organic wastes become naturally colonized by them, (2) they have good temperature tolerance and can live in organic wastes with a range of moisture contents. They are resilient earthworms, which can be handled readily and in mixed cultures with other species usually become dominant, so that even when systems begin with other species, they often end up with dominant *Eisenia* spp. The biology and ecology of *E. fetida* and *E. andrei*, when fed on animal manures or sewage sludge, has been investigated by several authors (Graff 1953 1974), Watanabe and Tsukamoto (1976), Hartenstein *et al.* (1979), Kaplan *et al.* (1980), Edwards (1988), Reinecke and Viljoen (1990), Elvira *et al.* (1996a), Domínguez and Edwards (1997), Domínguez *et al.* (1997), and Domínguez *et al.* (2000).

Under optimal conditions their life cycles (from freshly deposited cocoon through clitellate worm and the deposition of the next generation of cocoons) range from 45 to 51 days. The time for hatchlings to reach sexual maturity ranges from 21 to 30 days. Copulation in these species, which takes place in the organic matter, has been described by various authors since 1845 and has been observed more often than for any other megadrile species. Cocoon laying begins 48 hours after copulation and the rate of cocoon production is 0.35-1.3 per day. The hatching viability is 72-82 % and the incubation period ranges from 18 to 26 days. The number of young earthworms hatching from viable cocoons varies from 2.5 to 3.8 depending on the temperature. Maximum life expectancy has been found to be 4.5-5 years (Herlant-Meewis 1967) but average life survival was 594 days at 28° C and 589 days at 18° C (Michon 1957), although under natural conditions it may be considerably less than these figures.

Dendrobaena rubida (Savigny, 1826)

This is a temperate species of earthworm with a clear preference for organic soils and it also inhabits substrates such as decaying rotting wood and straw, pine litter, compost, peat, near sewage tanks and animal manures. Although some aspects of their biology have been investigated (Evans and Guild 1948, Gates 1972, Sims and Gerard 1985, Bengtsson *et al.* 1986, Cluzeau and Fayolle 1989, Elvira *et al.* 1996), it is not widely used in vermicomposting systems. *D. rubida* can complete a mean life cycle within 75 days. Its rapid maturation and high reproductive rate could make it a suitable species for vermicomposting. Compared to other vermicomposting species, *D. rubida* grows slowly although it reaches sexual maturity relatively quickly (54 days after hatching). Cluzeau and Fayolle (1989) found that it is sexually mature after 44±10 days. We found that the net reproductive rate for *D. rubida* was 2.06 hatchlings. Mature earthworm^{-1}.week^{-1} (Elvira *et al.*, 1996), although cocoon production rates by *D. rubida* reported in the literature are usually higher than those we reported (2.31 cocoons.week^{-1} (Bengtsson *et al.* 1986), and 3.22 cocoons. week^{-1} (Cluzeau and Fayolle 1989). Gates (1972) found that only one earthworm emerged from 75 % of the cocoons of *D. rubida*, with 2-4 hatchlings emerging from the remaining cocoons. According to Cluzeau and Fayolle (1989), one of the factors that contribute to the high fertility rate of *D. rubida* is that its reproduction may be facultatively biparental, amphimitic or uniparental, either by parthenogenesis (Omodeo 1952) or by self-fertilization (André and Davant 1972).

Dendrobaena veneta (Rosa, 1886)

This is a large species of earthworm with potential for use in vermiculture but which can also survive in soil (Satchell 1983), although it is not very prolific and does not grow very rapidly (Edwards 1988, and Viljoen *et al.* 1991). Of the species that have been studied for vermiculture, it is probably the least suitable species for use in organic waste processing or vermicomposting, although it does grow rapidly and may have some potential for protein production.

D. veneta can tolerate much wider moisture ranges than many other species and has a preference for mild temperatures (15-25° C). Its life cycle can be completed in 100-150 days, with 65 days as the average time to reach sexual maturity. Mean cocoon production is 0.28 per day, but the hatching viability seems to be very low (20 %) and the mean cocoon incubation period is 42 days. The mean number of earthworms hatching from each viable cocoon is about 1.10 (Lofs-Holmin 1986, Viljoen *et al.* 1991 and 1992, Muyima *et al.* 1994).

Lumbricus rubellus Hoffmeister, 1843

This species is commonly found in moist soils particularly those to which animal manures or sewage solids have been applied (Cotton and Curry 1980 a and b). In surveys of commercial earthworm farms in the US, Europe and Australia, earthworms that were sold under the name *L. rubellus* were all *E. fetida* or *E. andrei* (Edwards and Bohlen 1996).

L. rubellus has a relatively long life cycle (120-170 days), with a slow growth rate and a long maturation time (74-91 days) (Cluzeau and Fayolle 1989, and Elvira *et al.* 1996 b). The net reproductive rate we estimated to be 0.35 hatchlings earthworm^{-1}.week^{1}, due to the low cocoon production rate (0.54 cocoons. week^{-1}) and only one earthworm emerging from each cocoon (Elvira *et al.* 1996 b). Other researchers have recorded cocoon production rates for this species ranging from 0.49 (Cluzeau and Fayolle 1989) to 1.75 cocoons. week^{-1} (Evans and Guild 1948).

The low maturation and reproductive rates suggest that it is not an ideal earthworm for vermicomposting, although its size and vigour could make it of interest as fish bait or for land improvement. Moreover, *L. rubellus* is not an opportunistic species, with obligatory biparental reproduction (Sims and Gerard 1985), which contributes to its low reproductive rates.

Tropical species

Eudrilus eugeniae (Kinberg, 1867)

This earthworm species belonging to the Eudrilidae is native of Africa but has been bred extensively in the USA, Canada and elsewhere, for the fish bait market, where it is commonly called the "African nightcrawler". It is a large earthworm that grows extremely rapidly and is relatively prolific when cultured and under optimum conditions could be considered as an ideal species for animal feed protein production. Its main disadvantages are its narrow temperature tolerance and sensitivity to handling. *E. eugeniae* has high reproduction rates (Bano and Kale 1988, and Edwards 1988), and is capable of decomposing large quantities of organic wastes rapidly and incorporating them into the topsoil (Neuhauser *et al.* 1979 and 1988, Edwards 1988, Kale and Bano 1988). The life cycle of *E. eugeniae* ranges from 50-70 days and its life span can be 1-3 years. This species is more productive in terms of rates of growth than many other earthworm species and would seem to be a suitable candidate for vermicomposting systems, in regions where maintaining its optimal temperature of 25° C is both feasible and economic. Although the large size of *E. eugeniae* makes it much easier to handle and harvest, than commonly-used species such *E. fetida* and *P. excavatus*, it is much more sensitive to disturbance and handling and may occasionally migrate from breeding beds. However because it has been grown commercially for fish bait for a long time in the U.S. this is evidence that it is comparatively easy to rear. It is probably one of the two preferred species, together with *P. excavatus*, for vermiculture and vermicomposting in tropical climates (Domínguez *et al.* 2001).

Perionyx excavatus Perrier, 1872

Perionyx excavatus is an earthworm belonging to the Megascolecidae commonly found over a large area of tropical Asia (Stephenson 1930, and Gates 1972), although it has also been transported to Europe and North America. This is an epigaeic species which lives solely in organic wastes, high moisture contents. Adequate amounts of suitable organic material are required for its populations to become fully established and to process organic wastes efficiently. The life cycle of *P. excavatus* takes 40-71 days from hatching to maturity. This species prefers high temperatures and may die at temperatures below 5°C. *P. excavatus*, with about 90 % hatching rate and 1.1 hatchlings per cocoon have a net reproductive rate of nearly 20 cocoons week^{-1} (Edwards and Bohlen 1996).

Pheretima elongata (Perrier, 1872)

This megascolecid earthworm species has been tested for use in vermicomposting organic solids, including municipal and slaughterhouse wastes, human, poultry and dairy manures, and mushroom compost, in India. A project in India using this species claimed to have a commercially viable facility for the "vermistabilization" of 8 tons of organic solid waste day^{-1}. These workers developed a "vermifilter" (packed with vermicompost and live earthworms) which produces reusable water from sewage sludge, manure slurries and organic waste-waters from food-processing (Edwards and Bohlen 1996). *P. elongata* appears to be restricted to tropical regions and may not survive severe winters.

Table 1 summarizes some aspects of the biology of the vermicomposting species. A comparison of the duration of the life cycles and the reproductive potential of the earthworm species suitable for vermicomposting is presented in Figures 1 and 2 respectively.

Figure 1. Mean cocoon production of some of the earthworm species suitable for vermicomposting.

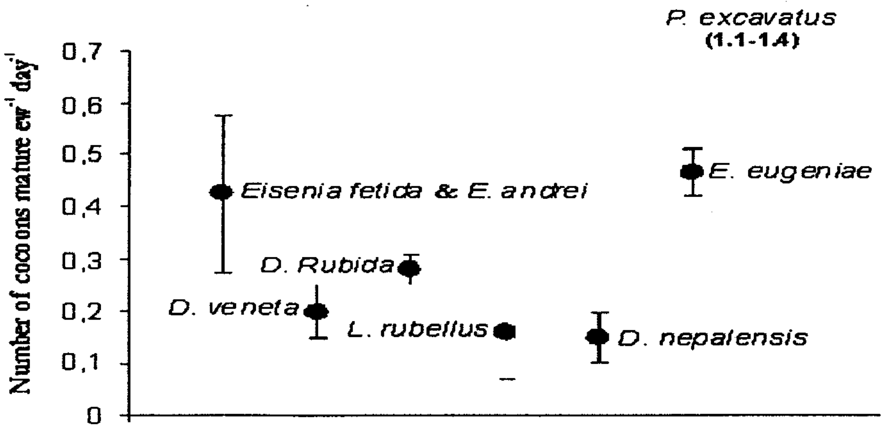
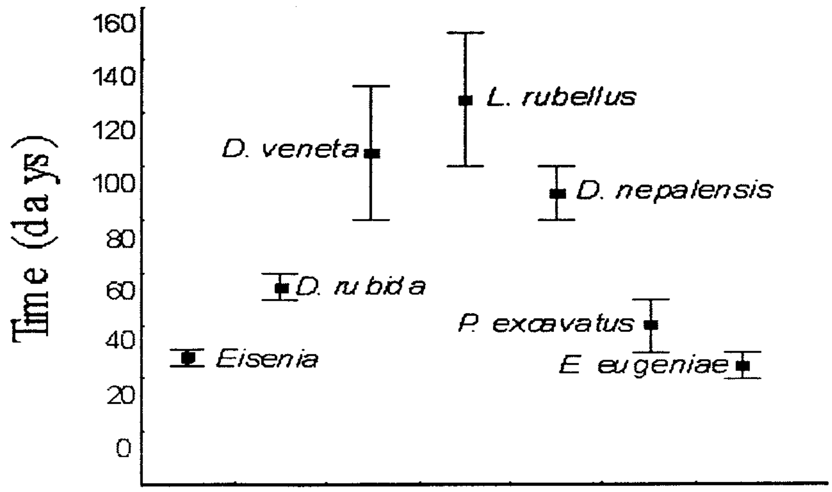


Figure 2. Length (days) of the life cycle of the earthworm species suitable for vermicomposting.



INFLUENCE OF ENVIRONMENTAL FACTORS ON SURVIVAL AND GROWTH OF EARTHWORMS

Cocoon production, rates of development and growth of earthworms, are critically affected by environmental conditions. Those species of earthworms that can be used in vermicomposting are relatively tolerant of the varied environmental conditions in organic wastes, so relatively simple low-management windrow or ground bed systems have been used extensively in the past to process wastes. However, it has been more recently clearly demonstrated that earthworms have well-defined limits of tolerance to certain parameters, such as moisture and temperature, and that the wastes are processed much more efficiently under a relatively narrow range of favourable chemical and environmental conditions. If these limits are greatly diverged from, the earthworms may move to more suitable zones in the waste, leave the waste, or die, so that the wastes are processed only slowly.

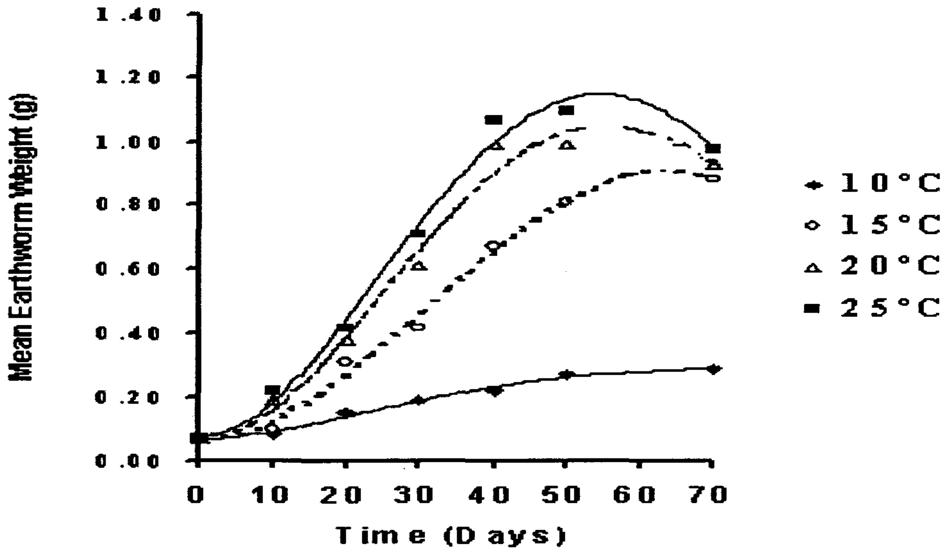
Temperature

Earthworms exhibit fairly complex responses to changes in temperature. Neuhauser *et al.* (1988) studied the potential of several species of earthworms to grow in sewage sludge and they concluded that all these species have optimum temperatures for growth ranging between 15 and 25° C. In these studies, cocoon production was restricted more by temperature than by growth and the species studied produced most of the cocoons at 25° C. Edwards (1988) studied the life cycles and optimal conditions for survival and growth of *E. fetida, D. veneta, E. eugeniae*, and *P. excavatus*. Each of these four species differed considerably in terms of their responses and tolerance to different temperatures. The optimum temperature for *E. fetida* was 25° C, and its temperature tolerance was between 0 and 35° C (Figure. 3). *Dendrobaena veneta* had a rather low temperature optimum and rather less tolerance to extreme temperatures. The optimum temperatures for *E. eugeniae* and *P. excavatus* were around 25° C, but they died at temperatures below 9° C and above 30° C. Optimal temperatures for cocoon production were much lower than those for growth for all these species.

Soil temperatures below 10° C generally resulted in reduced or no feeding activity and below 4° C, cocoon production and development of young earthworms ceased completely (Edwards and Bohlen 1996). In extreme conditions, earthworms tend to hibernate and migrate to deeper layers of the windrow or soil for protection. It appears that earthworms can acclimate to temperature in autumn and survive the winter, but they cannot survive long when exposed to freezing conditions.

The unfavourable effect of high temperatures (above 30° C) on most species of earthworms is not entirely a direct effect; these warm temperatures also promote chemical and microbial activities in the substrate and the increased microbial activity tends to consume the available oxygen with negative effects on the earthworms.

Figure 3. Growth of the earthworm *Eisenia fetida* at different temperatures



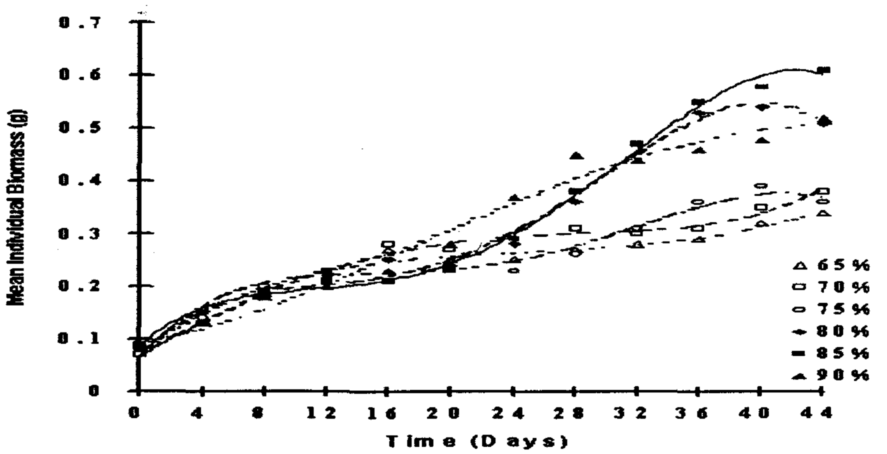
Moisture Content

There is a relationship between the moisture content in organic wastes and the growth rate of earthworms. In vermicomposting systems, the optimum range of moisture contents has been reported to be between 50 to 90 %. *E. fetida* can survive in moisture ranges between 50 and 90 % (Edwards 1988, and Sims and Gerard 1985), but grows more rapidly between 80 and 90 % in animal wastes (Edwards 1988). Reinecke and Venter (1985) reported that the optimum moisture content for *E. fetida* was above 70 % in cow manure, but *E. andrei* cultured in pig manure grew and matured best between 65 and 90 % moisture content, with 85 % being the optimum (Figure 4) (Domínguez and Edwards 1997). According to Reinecke and Venter (1985), it seems likely that a lowering of the growth rate due to low moisture conditions can also retard sexual development so that earthworms of the same age could develop clitella at different times under different moisture conditions.

pH

Epigaeic earthworms are relatively tolerant to pH, but when given a choice in the pH gradient, they move towards the more acid material, with a pH preference of 5.0 (Figure 5). However, earthworms will avoid acid soils of pH less than 4.5, and prolonged exposure to such soils could have lethal effects (Edwards and Bohlen 1996). Minor increases in acidity, caused by addition of fresh wastes to the vermicomposting bed, can be neutralized by the intestinal calcium secretions of earthworms and excreted ammonia.

Figure 4. Growth of the earthworm *Eisenia andrei* in pig manure a different moisture contents



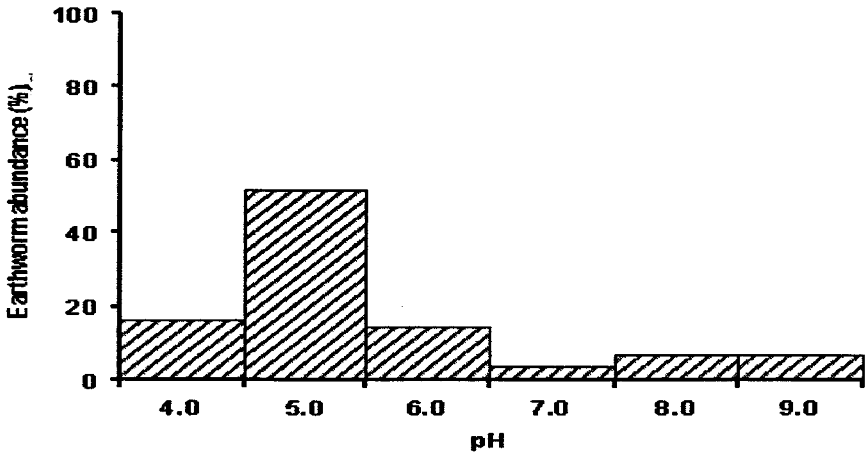
Aeration

Earthworms have no specialized respiratory organs, and oxygen diffuses in through the body wall and carbon dioxide diffuses out. However, earthworms are very sensitive to anaerobic conditions and their respiration rates are depressed in low oxygen concentrations, around 55 to 65 % (*e.g.*, at oxygen levels of 0.25 its normal partial pressure (Edwards and Bohlen 1996) and feeding activity might be reduced under these sub-optimal conditions. Individuals of *E. fetida* have been reported to migrate in large numbers from a water-saturated substrate in which the oxygen has been depleted, or in which carbon dioxide or hydrogen sulfide has been accumulated. However, they can live for long periods in aerated water such as that in trickling filters.

Ammonia

Earthworms are very sensitive to ammonia and cannot survive in organic wastes containing high levels of this cation (*e.g.*, fresh poultry litter). They also die in organic wastes with large amounts of inorganic salts. Both ammonia and inorganic salts have very sharp cutoff points between toxic and nontoxic, *i.e.*, <1 mg/g of ammonia (Figure 6) and <0.5% salts. However, organic wastes containing large amounts of ammonia can become acceptable after its removal by a period of composting, or when both excessive ammonia and salts can be washed out of the waste.

Figure 5. pH preferences of the earthworm *Eisenia fetida*

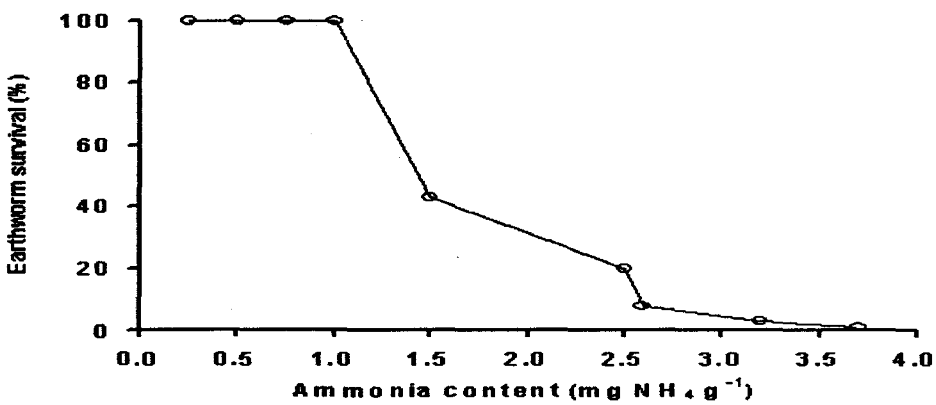


Outside the limits of these environmental parameters, both earthworm activity and the rates of organic waste processing decrease dramatically. For maximum vermicomposting efficiency, wastes should be conditioned to make them suitable for vermicomposting. The optimal conditions for breeding *E. fetida* and *E. andrei* are summarized in Table 2 and these characteristics do not differ too much from those most suitable for other earthworm species.

Earthworm population density is known to affect rates of earthworm growth and reproduction. Even when the physical-chemical characteristics of the wastes are ideal for vermicomposting, problems can develop due to earthworm overcrowding. Reinecke and Viljoen (1990) in studies with *E. fetida* reared in cow manure and Domínguez and Edwards (1997) studying the growth and reproduction of *E. andrei* in pig manure, reported that when grown at different population densities, the earthworms in the crowded dishes grew more slowly and ended with a lower final bodyweight, although the total weight of earthworm biomass produced per unit of waste was greater. Maturation rates were also affected by the population; earthworms of the same age developed a clitellum at different times in cultures with different stocking rates.

When environmental conditions are maintained at adequate ranges, a maximum yield of 10 dry unit weights of earthworm biomass can be expected from an initial 100 units (dry weight) of substrate, independent of nitrogen concentration, when a minimum of about 1 % or more N is initially present (Hartenstein 1983, and Edwards 1988), and although this conclusion is based on laboratory experiments, a similar yield can be expected from field systems that are well managed.

Figure 6. Survival of *Eisenia fetida* at different ammonia contents.



It is possible that organic waste ingestion stops when a critical level of humified material appears, rich in free-radicals and non-ingestible contents, despite the remaining abundance of oxidizable carbon (Hartenstein 1983, and Hartenstein and Neuhauser 1985). This may account for the relatively low biomass of earthworms in the tropics despite the high availability of organic carbon from vegetation and the rapid rates of soil and organic matter turnover.

Effect of diet on the growth and reproduction of earthworms

Earthworms fragment organic wastes with a grinding gizzard. This promotes very high microbial activity; moreover, earthworms use microorganisms for nutrients rather than the organic matter. Vermicomposts can be produced from almost all kinds of organic waste with suitable pre-processing and controlled processing conditions. However the growth and reproduction of earthworms depends very much on the quality of their food resources in terms of their potential to increase microbial activity. Depending on this quality, earthworms will invest more energy either in growth or in reproduction. For example, studying the effect of different residual bulking agents (*e. g.*, paper, cardboard, grass clippings, pine needles, sawdust, and food wastes), mixed with sewage sludge (1:1 dry weight), on the growth and reproduction of *Eisenia andrei,* we found that the maximum earthworm weights achieved and the highest growth rates occurred in the mixture with food waste (755±18 mg and 18.6±0.6 mg day^{-1}, respectively), whereas the smallest earthworm size and the lowest growth rate occurred in the mixture of sewage sludge with sawdust (572±18 mg and 11±0.7 mg day^{-1}, respectively). However, the earthworms reproduced much faster in the paper and cardboard mixtures (2.82±0.39 and 3.19±0.30 cocoons $earthworm^{-1}$ $week^{-1}$, respectively), compared to reproduction in the control with sewage sludge alone (0.05±0.01 cocoons $earthworm^{-1}$ $week^{-1}$) (Figure 7) (Domínguez *et al.* 2000).

ECOLOGY OF VERMICOMPOSTING: A CASE STUDY

An experiment at the University of Vigo aimed at studying a continuous vermicomposting system with different mixtures of pig manure slurries and agroforestry by-products. This research project analyzed the effects of earthworm populations on the process and also evaluated characteristics of the vermicomposts produced after different periods of time. The vermicomposting boxes were sampled monthly during a year, and numbers and total weights of earthworms and cocoons were recorded and also several physical and chemical parameters were measured.

Population dynamics of earthworms

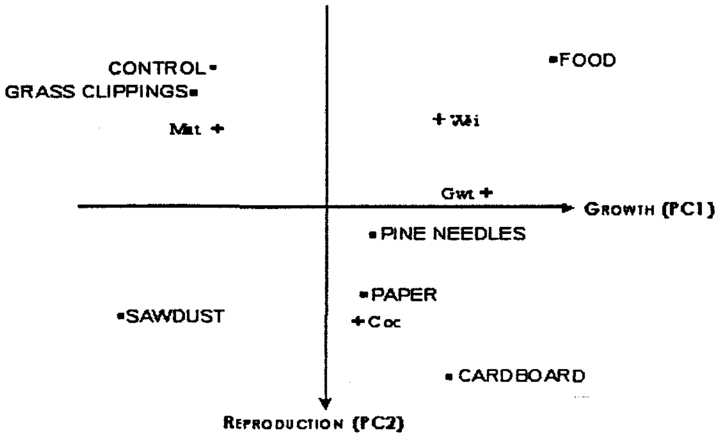
In the continuous vermicomposting systems, a decrease in earthworm biomass was observed at the start of the experiment; this was more marked in the mixtures of pig slurry with pine bark and pine needles. Later the earthworm populations recovered and their biomass gradually increased to final values that were greater than the initial ones (Figure 8, Plare 2). One possible cause is that in microcosm experiments earthworms are unable to find suitable habitats and can suffer an initial stress. As a consequence of this, the effects of earthworms on the decomposition of organic matter were greater during the final stages of the process when the earthworm populations were more conditioned and active.

pH during vermicomposting

The pH of the pig slurry used in the vermicomposting experiments ranged from 8.2 to 8.7. The vermicompost obtained at different times was slightly acid, with values similar to the parent waste, proving that earthworms did not affect the pH values to any great extent (Figure 9). The effects of the earthworms on pH during vermicomposting is probably related to increases in the mineral nitrogen content of the substrates, changes in the ammonium-nitrate equilibrium, and accumulation of organic acids from microbial metabolism or from the production of fulvic and humic acids during decomposition.

Figure 7. Effect of the diet on the growth and reproduction of the earthworm *Eisenia andrei*.

Position of different diet treatments in the plan defined by factorial axes representing growth and reproduction of the earthworm *Eisenia andrei*. Mat: sexual maturity; Wei: earthworm weight. Gwt: earthworm growth; Coc: cocoon production. PC1 represents 46.5% of total inertia and PC2 36.87%.



Carbon mineralization during vermicomposting

As other members of the organic matter decomposer community, earthworms can assimilate carbon from the most recently deposited organic matter fractions, consisting mainly of easily-degradable substances. In all cases the degradation process resulted in carbon losses by mineralization which produced a decrease in the amounts of total organic carbon and in the carbon contributions to the organic matter, which was much higher in the final stages of decomposition when the earthworm populations were bigger and more active (Figure 10). Although earthworms consume and process large amounts of organic matter, their contributions to the total heterotrophic respiration is very low due to their poor assimilation efficiency and only when there are large active earthworm populations, as in vermicomposting systems, can they contribute to an appreciable extent to the heterotrophic respiration.

Nitrogen transformations in vermicomposting

Earthworms had a great impact on nitrogen transformations in the pig manure by enhancing nitrogen mineralization, so that most mineral nitrogen was retained as nitrate. The net total nitrogen, in all treatments and times, decreased; losses being more marked during the final stages when earthworm activity was higher. The different nitrogen fractions followed trends similar to the total nitrogen. In all treatments, during the final stages of the process, when the earthworm population was bigger and more active, important reductions in organic nitrogen content and a high nitrification rate were noted (Figure 11). This implies that earthworm (*Eisenia andrei* in this case), modified conditions in the manure that favoured nitrification, resulting in the rapid conversion of ammonium into nitrates. Similar results have been reported by Hand *et al.* (1988) who found that *Eisenia fetida* in cow slurry increased the nitrate concentration of the substrate.

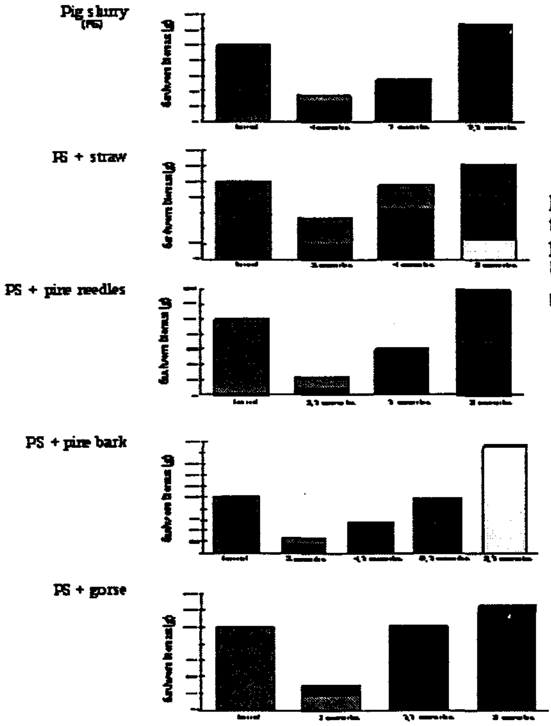


Figure 8. Evolution of earthworm biomass after the establishment of a vermicomposting system with pig slurry mixed with different agro-forestry by-products.

Earthworm biomass decreased at the start of the experiment; later the earthworm populations recovered and their biomass gradually increased to final values that were greater than the initial ones.

Figure 9. Effects of the earthworms on pH during vermicomposting.

The vermicompost obtained at different times was slightly acid, with similar values to the parent waste, proving that earthworms did not affect the pH values to any great extent.

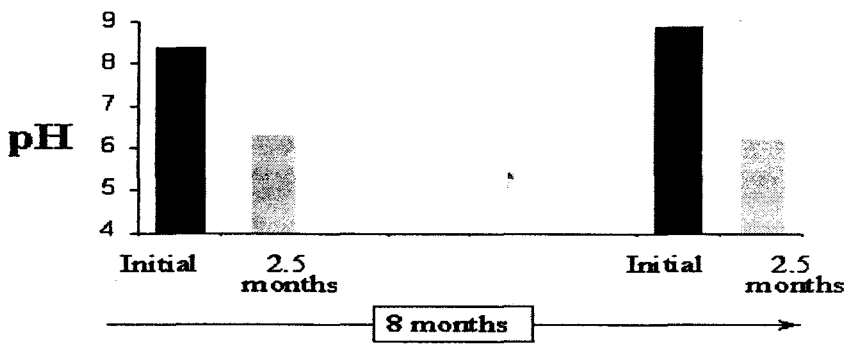
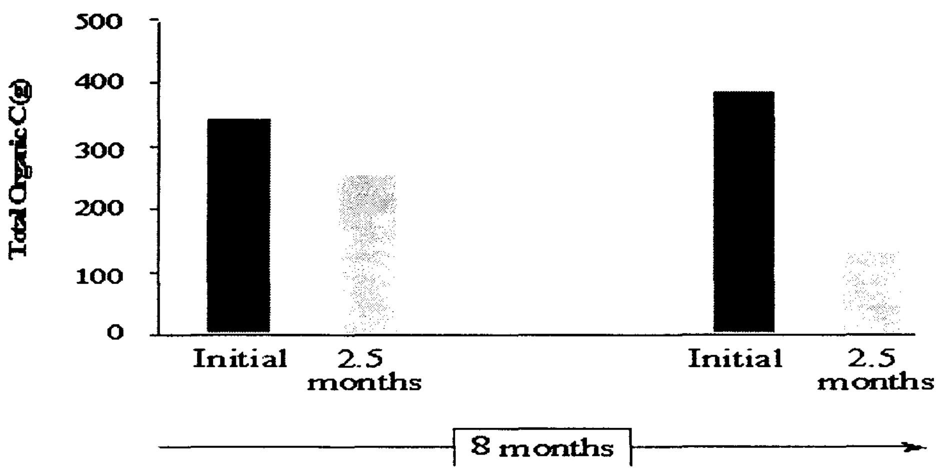


Figure 10. Carbon mineralization during vermicomposting.

The degradation process resulted in carbon losses by mineralization which produced a decrease in the amounts of total organic carbon and in the carbon contributions to the organic matter, which was much higher in the final stages of decomposition when the earthworm populations were bigger and more active.



Humification during vermicomposting

Saviozzi *et al.* (1988) reported that organic wastes, to be compatible with their agricultural uses and to avoid adverse effects on plant growth, must be transformed into a humus-like material and become stabilized. In this case study, decreases in the carbon from fulvic acids and increases in the percentages of the carbon from humic acids were observed throughout the vermicomposting process, and this was also much more marked at the end of the process (Figure 12), so clearly earthworm activity accelerates humification of organic matter. Moreover, during Vermicomposting, the humic materials increased from 40 to 60 percent, which was more than the values obtained in a composting process using the same materials. Humification processes are enhanced not only by the fragmentation and size reduction of the organic matter, but also by the greatly increased microbial activity within the intestines of the earthworms and by aeration of the soil through earthworm movement and feeding.

Stability of the organic wastes and maturity of the vermicomposts

The stability and maturity of organic wastes, which implies a potential for the development of beneficial effects to plants when they are used as growth media, can be determined by plant germination experiments and growth bioassays (Chen and Inbar 1993). In this example, the germination percentages of *Lepidium sativum* indicated that the initial organic matter mixtures were toxic to the plants, probably due to their high ammonium content, but this toxicity was gradually removed through the vermicomposting process. Moreover, the results obtained for the germination index (which combined germination percentages and coleoptile elongations), demonstrated a beneficial effect of the earthworms, with the highest values of this index recorded during the final stages of the process, when the earthworm populations were largest (Figure 13).

Vermicomposting and heavy metal availability

It is important to know the changes in total and available contents of heavy metals in the organic matter during the vermicomposting process, because they may cause problems in some animal manures, sewage sludges, and industrial organic wastes. In this experiment, although as a consequence of carbon losses by mineralization during vermicomposting, the total amounts of heavy metals increased (between 25 and 30 %), the amounts of bioavailable heavy metals tended to decrease with a decrease of between 35 and 55 % in the bioavailable metals in two months (Figure 14). Similar results were reported in other studies for both composting and vermicomposting and this implies a lower availability of these elements for plants from vermicomposts. During vermicomposting, heavy metals tend to form complex aggregates with the humic acids and the most polymerized organic fractions.

Figure 11. Nitrification during vermicomposting.

During the final stages of the process, when the earthworm population was bigger and more active, important reductions in organic nitrogen content and a high nitrification rate were noted.

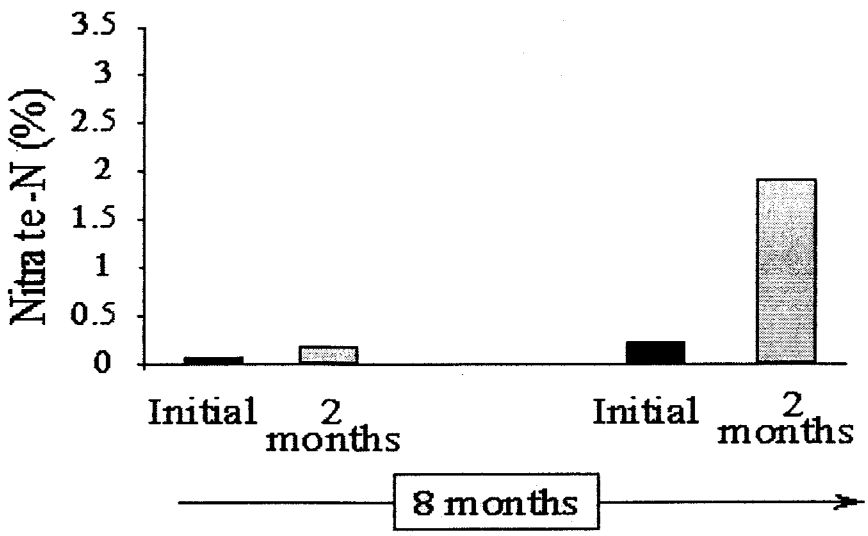


Figure 12. Humification during vermicomposting.

Decreases in the carbon from fulvic acids and increases in the percentages of the carbon from humic acids were observed throughout the vermicomposting process and this was also much more marked at the end of the process; clearly earthworm activity accelerates humification of organic matter.

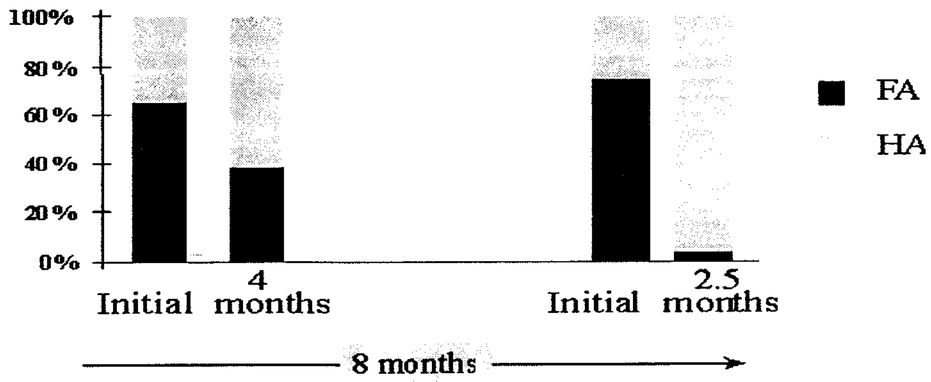
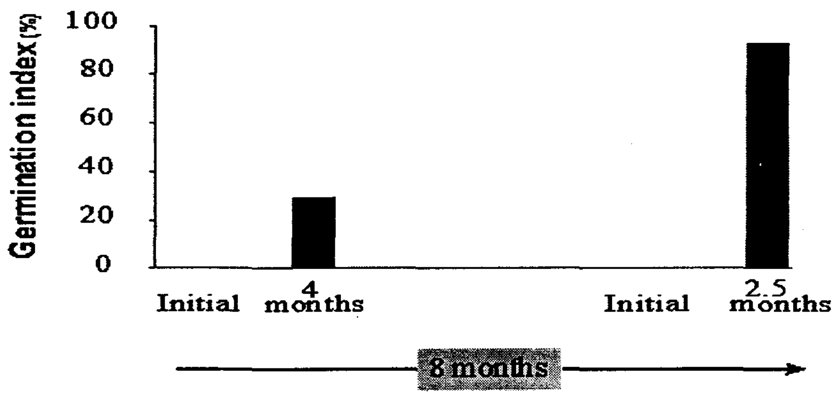


Figure 13. Germination index of *Lepidium sativum* in vermicompost from pig manure.

The results obtained for the germination index (which combined germination percentages and coleoptile elongations) demonstrated a beneficial effect of the earthworms, with the highest values of this index recorded during the final stages of the process when the earthworm populations were largest and more active.



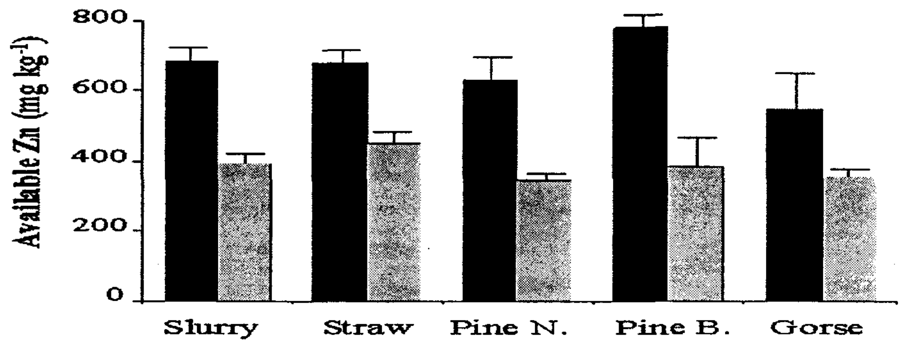
Vermicomposting and pathogen destruction

Preliminary research in our laboratory has shown that vermicomposting involves a great reduction in populations of human pathogenic microorganisms, as in composting. It is generally accepted that the thermophilic stage of the composting process eliminates pathogenic organisms, but we have shown that human pathogens do not survive vermicomposting. After 60 days of vermicomposting, amounts of faecal coliform bacteria in biosolids dropped from 39,000 MPN/g to 0 MPN/g. In that same time period, *Salmonella* sp. dropped from <3 MPN/g to <1 MPN/g. Similar results have been reported by Eastman (1999) and also other authors for faecal coliforms, *Salmonella* sp., for enteric viruses, and for helminth ova (Edwards *et al.*, in press).

SOIL FOODWEBS IN THE VERMICOMPOSTING SYSTEM

Earthworms participate in soil functions through the drilosphere which is defined as the space of interactions between earthworms, physical structure and the whole microbial and invertebrate community of the soil (Lavelle *et al.* 1998), as a result of organic matter digestion processes and the creation of soil structures. The overall composition, structure, and the relative importance of the drilosphere are clearly determined by environmental conditions, soil characteristics and the quality of the organic matter inputs. In vermicomposting, complex interactions between the organic matter, microorganisms, earthworms and other soil invertebrates, result in the rapid bio-oxidation and stabilization of the organic matter. Vermicomposting systems sustain complex food webs, and at the same time, modify the chemical forms of several nutrient elements into longer-lived organic compounds, which are important for nutrient dynamics (Domínguez *et al.* 1997).

Figure 14. Heavy metal availability (extractable with AB-DTPA) in vermicompos from pig slurry mixed with different agro-forestry by-products.
In this experiment, although as a consequence of the carbon losses by mineralization during vermicomposting, th total amounts of heavy metals increased (between 25-30 %), the amounts of bioavailable heavy metals tended to decrease with a decrease of between 35 % and 55 % in the bioavailable metals in two months.



Although populations of some sensitive organisms may be reduced drastically or eliminated during vermicomposting, the substrate maintains an active community of decomposer organisms, which, in addition to earthworms, includes enchytraeids, nematodes, springtails, mites, protozoa and large populations of microorganisms. The complex foodwebs in the vermicomposting systems can be represented by a pyramid with primary, secondary, and tertiary level consumers. The base of the pyramid, the source of energy, is composed of decaying organic matter, including plant and animal residues. In the same way as in soil, the spatial scales at which soil organisms act in a vermicomposting system are determined mainly by their size, number, and mode of operation. Swift *et al.* (1979) recognized three spatial scales based on animal size: micro, meso and macro-invertebrates. At the microflora microscale there are basically bacteria (unable to move large distances except if transported by water or larger soil organisms), fungi (in which hyphal growth provides the capacity to colonize new zones), and actinomycetes. Concomitantly, still at a microscale but gradually increasing in size and spatial influence, the micro foodweb includes microfauna, such as nematodes, protozoa and rotifers that feed primarily on microorganisms. At the mesoscale there are larger organisms such as enchytraeids and micro and mesoarthropods that feed on decaying organic matter, microorganisms and microinvertebrates, and are important in facilitating nutrient cycling and the small-scale dispersal of microorganisms. Finally at the macroscale, there is the main component of the vermicomposting system, the earthworms, which feed on and disperse microorganisms. As they feed on decaying organic matter, their burrowing and tunnelling activitys aerates the substrate and enables water, nutrients and oxygen to filter through it; their feeding activities increase the surface area of organic matter for microorganisms to act upon. As decomposers die, more food is added to the foodweb for other decomposers.

As organic matter passes through the earthworm's gizzard, it is finely-ground prior to digestion. Then, digestive microorganisms and possibly enzymes, and other fermenting substances continue the breakdown process within the gut. The organic matter passes out of the earthworm's body in the form of casts, the vermicompost, which are of a rich and fine quality.

Earthworms can exert an influence on soil microorganisms and invertebrate populations directly or indirectly via comminution, burrowing, casting, grazing and dispersal. Not only does the physico-chemical and biological status of the soil change during the course of these activities, but the characteristics of the drilosphere may also be dramatically altered (see reviews by Brown 1995, and Doube and Brown 1998). The drilosphere is the soil system influenced directly or indirectly by earthworm activities (Lavelle 1988), whether in the gut of the earthworm (internal processes), or in its burrows and casts (external processes). As a consequence, the entire soil invertebrate community plays an important role in degradation through its interactions with soil microorganisms.

Since active earthworm beds or vermicomposting systems are teem with an enormous variety of microorganisms and invertebrates, they provide ideal sites for complete and effective inoculation of the organic wastes with complex communities of beneficial soil organisms. This may be especially important for producing plant container media and for soils that have been intensively chemically managed and/or are impoverished. As our understanding of soil ecology increases, determination of the structure of decomposer food webs in organic amendments may become an important predictive tool in evaluating their potential qualities and value.

REFERENCES

Allevi L, Citterio B, Ferrari A (1987) Vermicomposting of rabbit manure: modifications of microflora. In de Bertoldi M, Ferranti MP, L'Hermite P, Zucconi F (eds.) Compost: Production, Quality and Use. Elsevier Applied Science, Amsterdam, pp 115-126.

André F, Davant N (1972) L'autofécondation chez les lombriciens. Observation d'un cas d'auto-insémination chez *Dendrobaena rubida subrubicunda* Eisen. Séance, 12 du Décembre: 725-728.

Bano K, Kale RD (1988) Reproductive potential and existence of endogenous rhythm in the reproduction of the earthworm *Eudrilus eugeniae*. Proc. Zool. Soc. (Calcutta) 38: 9-14.

Bouché MB (1977) Stratégies lombriciennes. In: Lohm U, Persson T (eds.) Soil Organisms as Components of Ecosystems. Biol. Bull. 25: 122-132.

Butt KR (1993) Utilization of solid paper mill sludge and spent brewery yeast as a feed for soil-dwelling earthworms. Bioresource Technol 44: 105-107.

Chen Y, Inbar Y (1993) Chemical and spectroscopical analyses of organic matter transformations during composting in relation to compost maturity. In: Hoitink HAJ, Keener HM (eds.) Science and Engineering of Composting: Design, Environmental, Microbiological and Utilization Aspects. Renaissance Publication. Worthington, Oh, pp 622-644.

Cluzeau D, Fayolle L (1989) Croissance et fécondité comparées de *Dendrobaena rubida tenuis* (Eisen, 1874), *Eisenia andrei* (Bouché, 1972) et *Lumbricus rubellus rubellus* (Hoffmeister, 1843) (Oligochaeta, Lumbricidae) en élevage contrôlé. Rev. Ecol. Biol. Sol 26: 111-121.

Cotton DCF, Curry JP (1980 a) The effects of cattle and pig slurry fertilizers on earthworms (Oligochaeta, Lumbricidae) in grassland managed for silage production. Pedobiologia 20: 181-188.

Cotton DCF, Curry JP (1980 b) The response of earthworm populations (Oligochaeta, Lumbricidae) to high applications of pig slurry. Pedobiologia 19: 425-438.

Domínguez J, Briones MJI, Mato S (1997) Effect of the diet on growth and reproduction of *Eisenia andrei* (Oligochaeta, Lumbricidae). Pedobiologia 41: 566-576.

Domínguez J, Edwards CA (1997) Effects of stocking rate and moisture content on the growth and maturation of *Eisenia andrei* (Oligochaeta) in pig manure. Soil Biol Biochem 29: 743-746.

Domínguez J, Edwards CA, Ashby J (2001) The biology and ecology of *Eudrilus eugeniae* (Kinberg) (Oligochaeta) bred in cattle waste. Pedobiologia 45: 341-353.

Domínguez J, Edwards CA, Webster M (2000) Vermicomposting of sewage sludge: effect of bulking materials on the growth and reproduction of the earthworm *Eisenia andrei*. Pedobiologia 44: 24-32.

Eastman B (1999) Achieving pathogen stabilization using vermicomposting. Biocycle November: 62-64.

Edwards CA (1988) Breakdown of animal, vegetable and industrial organic wastes by earthworms. In: Edwards CA, Neuhauser EF (eds.) Earthworms in Waste and Environmental Management. SPB, The Hague. pp 21-31.

Edwards CA (1998) The use of earthworms in the breakdown and management of organic wastes. In: Edwards CA (ed.) Earthworm Ecology. CRC Press, Boca Raton, FL, pp 327-354.

Edwards CA, Bohlen PJ (1996) Biology and Ecology of Earthworms. Chapman and Hall, London. 426 pp.

Edwards CA, Burrows I (1988) The potential of earthworm composts as plant growth media. In: Edwards CA, Neuhauser E (eds.) Earthworms in Waste and Environmental Management. SPB Academic Press, The Hague, The Netherlands, pp 21-32.

Edwards CA, Domínguez J, Neuhauser EF (1998) Growth and reproduction of *Perionyx excavatus* (Perr.) (Megascolecidae) as factors in organic waste management. Biol. Fertil. Soils 27: 155-161.

Elvira C, Domínguez J, Sampedro L, Mato S (1995) Vermicomposting for the paper pulp industry. BioCycle ??: 62-63

Elvira C, Domínguez J, Briones MJI (1996 a) Growth and reproduction of *Eisenia andrei* and *E. fetida* (Oligochaeta, Lumbricidae) in different organic residues. Pedobiologia 40: 377-384.

Elvira C, Domínguez J, Mato S (1996 b) The growth and reproduction of *Lumbricus rubellus* and *Dendrobaena rubida* in cow manure. Mixed Cultures with *Eisenia andrei*. Appl. Soil Ecol. 5: 97-103.

Elvira C, Sampedro L, Dominguez J, Mato S (1997) Vermicomposting of wastewater sludge from paper pulp industry with nitrogen rich materials. Soil Biol Biochem 29: 759-762.

Evans AC, Guild DWMcL (1948) Studies on the relationships between earthworms and soil fertility. V. On the life cycles of some British Lumbricidae. Ann. Appl. Biol. 35: 471-484.

Gates GE (1972) Burmese Earthworms. An introduction to the systematics and biology of megadrile oligochaetes with special reference to Southeast Asia. Trans. Am. Philosoph. Soc. N. S. 62: 1-326.

Graff O (1953) Die Regenwürmer Deutschlands. Schrift. Forsch. Land. Braunschweig-Volk. 7: 81-91.

Graff O (1974) Gewinnung von Biomasse aus Abfallstoffen durch Kultur des Kompostregenwurms *Eisenia foetida* (Savigny, 1826). Landaubforsch. 2: 137-142.

Hand P, Hayes WA, Frankland JC, Satchell JE (1988) Vermicomposting of cow slurry. Pedobiologia 31: 199-209.

Hartenstein R (1983) Assimilation by *Eisenia fetida*. In Satchell JE (ed.) Earthworm Ecology. Chapman and Hall, Cambridge. pp 297-308.

Hartenstein R, Neuhauser EF (1985) Stabilization of activated sludge bioassay with *Eisenia fetida* and certain organic chemical characteristics. J. Water Pollut. Control Fed. 57: 419-421.

Hartenstein R, Neuhauser EF, Kaplan DL (1979) Reproductive potential of the earthworm *Eisenia foetida*. Oecologia 43 :329-340.
Kale RD, Bano K (1988) Earthworm cultivation and culturing techniques for production of Vee Comp. 83. EUAS. Mysore J. Agric. Sci. 2: 339-344.
Kaplan DL, Hartenstein R, Neuhauser EF, Malecki MR (1980) Physicochemical requirements in the environment of the earthworm *Eisenia foetida*. Soil Biol Biochem 12: 347-352.
Lakhani KH, Satchell JE (1970) Production by *Lumbricus terrestris* (L.). J. Anim. Ecol. 39: 473-492.
Lavelle P (1983) The structure of earthworm communities. In Satchell JE (ed.) Earthworm Ecology, from Darwin to Vermiculture. Chapman & Hall, London, pp 449-466.
Lavelle P (1988) Earthworm activities and the soil system. Biol Fertil Soils 6:237-251.
Lavelle P, Barois I (1984) Potential use of earthworms in tropical soils. Proc. Intl. Conf. Earthworms Waste Environ. Manage.
Lavelle P, Barois I, Blanchart E, Brown G, Brussaard L, Decaëns T, Fragoso C, Jimenez JJ, Kajondo KK, Martínez MA, Moreno A, Pashanasi B, Senapati B, Villenave C (1998) Earthworms as a resource in tropical agroecosystems. Nature & Resources 34: 26-41.
Lofs-Holmin A (1986) Processing of municipal sludges through earthworms (*Dendrobaena veneta*). Swed. J. Agric. Res. 16: 67-71.
Muyima NYO, Reinecke AJ, Viljoen SA (1994) Moisture requirements of *Dendrobaena veneta* (Oligochaeta), a candidate for vermicomposting. Soil Biol Biochem 26: 973-976.
Neuhauser EF, Kaplan DL, Hartenstein R (1979) Life history of the earthworm *Eudrilus eugeniae*. Rev Ecol Biol Sol 16: 525-534.
Neuhauser EF, Loehr RC, Malecki MR (1988) The potential of earthworms for managing sewage sludge. In: Edwards CA, Neuhauser EF (eds.) Earthworms in Waste and Environmental Management. SPB, The Hague, pp 9-20.
Omodeo O (1952) Cariologia dei Lumbricidae. Caryologia 4: 173-274.
Reinecke AJ, Venter JM (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 AJ, Viljoen SA (1990) The influence of worm density on growth and cocoon production of the compost worm *Eisenia fetida* (Oligochaeta). Rev Ecol Biol Sol 27: 221-230.
Reynolds J (1994) Earthworms of the world. Global diversity 4: 11-16.
Reynolds JW (1998) The status of earthworm biogeography, diversity, and taxonomy in North America revisited with glimpses into the future. In: Edwards CA (ed.) Earthworm Ecology. St. Lucie Press, Boca Raton, Florida. pp 15-36.
Satchell JE (1980) r worms and k worms: a basic for classifying lumbricid earthworm strategies. In Dindal DL (ed.) Soil Biology as related to Land use practices. PA Publishing, USA. pp 848-863.
Satchell JE (1983) Earthworm Ecology, from Darwin to Vermiculture. Chapman & Hall, London.
Sims RW, Gerard BM (1985) Earthworms. In: Kermack DM, Barnes RSK (eds.) Synopses of the British Fauna (New Series), nº 31. Published for the Linnean Society of London and the Estuarine and Brackish-water Sciences Association, London.
Stephenson J (1930) The Oligochaeta. Oxford University Press
Viljoen S., Reinecke AJ, Hartman L (1991) Life-cycle of the European compost worm *Dendrobaena veneta* (Oligochaeta). S. Afr. J. Zool. 26: 43-48.
Watanabe H, Tsukamoto J (1976) Seasonal change 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.
Wilson DP, Carlile WR (1989) Plant growth in potting media containing worm-worked duck waste. Acta Horticulturae 238: 205-220.

Table 1. Comparison of some aspects of the biology of the vermicomposting species

	Eisenia fetida	*Eisenia andrei*	*Dendrobaena rubida*	*Dendrobaena veneta*	*Lumbricus rubellus*
Colour	Brown and buff bands	Red	Reddish purple	Reddish and purple bands	Reddish brown
Size of adult worms	4-8 mm x 50-100mm	4-8 mm x 50-100mm	3-4 mm x 35-60mm	5-7 mm x 50-80mm	4 mm x 70-150 mm
Mean weight of adults	0.55 g	0.55 g	0.25 g	0.92 g	0.80 g
Time to maturity (days)	28-30	21-28	54	65	74-91
Number of cocoons day^{-1}	0.35-0.5	0.35-0.5	0.20	0.28	0.07-0.25
Mean size of cocoons	4.85 mm x 2.82 mm	4.86 mm x 2.64 mm	3.19 mm x 1.97 mm	3.14 mm x 1.93 mm	3.50 mm x 2.46 mm
Incubation time (days)	18-26	18-26	15-40	42.1	35-40
Hatching viability (%)	73-80	72	85	20	60-70
Number of worms $cocoon^{-1}$	2.5 - 3.8	2.5 - 3.8	1.67	1.10	1
Self fertilization	+	+	+	?	-
Life cycle (days)	45-51	45-51	75	100-150	120-170
Limits and Optimal T^a	25°C (0-35°C)	25°C (0-35°C)	?	25°C (15-25°C)	?
Limits and optimal moisture	80-85% (70-90%)	80-85% (70-90%)	?	75% (65-85%)	?

Table 1. Cont.

	Drawida nepalensis	*Eudrilus eugeniae*	*Perionyx excavatus*
Colour	?	Reddish brown	Reddish brown
Size of adult worms	?	5-7 mm x 80-190 mm	4-5mm x 45-70mm
Mean weight of adults	0.82 g	2.7 - 3.5 g	0.5-0.6 g
Time to maturity (days)	34-42	40-49	28-42
Number of cocoons day^{-1}	0.15	0.42-0.51	1.2-2.7
Mean size of cocoons	?	?	?
Incubation time (days)	24	12-16	18
Hatching viability (%)	75-88	75-84	90
Number of worms $cocoon^{-1}$	1.93	2-2.7	1-1.1
Self fertilization	+	-	?
Life cycle (days)	100-120	50-70	40-50
Limits and Optimal T^{a}	?	25°C (16-30°C)	25-37°C
Limits and optimal moisture	?	80% (70-85%)	75-85%

Table 2. Optimal conditions for breeding *E. fetida* and *E. andrei* in organic wastes.

Condition	Requirements
Temperature	15-20°C (limits 4-30°C)
Moisture content	80-90% (limits 60-90%)
Oxygen	Aerobicity
Ammonia content of the waste	Low: <1 mg g^{-1}
Salt content	Low: <0.5%
PH	5-9