
20 State-of-the-Art and New Perspectives on Vermicomposting Research

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CONTENTS

Introduction	402
What is Vermicomposting?	402
Earthworms	403
Earthworm Life Histories	403
Earthworm Species Suitable for Vermicomposting	404
Temperate Species	405
<i>Eisenia fetida</i> (Savigny, 1826) and <i>Eisenia andrei</i> (Bouché, 1972)	405
<i>Dendrobaena rubida</i> (Savigny, 1826)	405
<i>Dendrobaena veneta</i> (Rosa, 1886)	406
<i>Lumbricus rubellus</i> (Hoffmeister, 1843)	406
Tropical Species	406
<i>Eudrilus eugeniae</i> (Kinberg, 1867)	406
<i>Perionyx excavatus</i> Perrier, 1872	407
<i>Pheretima elongata</i> (Perrier, 1872)	407
Influence of Environmental Factors on Survival and Growth of Earthworms	407
Temperature	409
Moisture Content	409
pH	410
Aeration	410
Ammonia	410
Effects of Diet on the Growth and Reproduction of Earthworms	411
Ecology of Vermicomposting: A Case Study	411
pH during Vermicomposting	412
Carbon Mineralization during Vermicomposting	412
Nitrogen Transformations during Vermicomposting	412
Vermicomposting and Heavy Metal Availability	413
Humification during Vermicomposting	414
Stability of Organic Wastes and Maturity of the Vermicomposts	414
Vermicomposting and Human Pathogen Destruction	414
Soil Food Webs in the Vermicomposting System	414
Applications of Vermicomposting	416
New Perspectives in Vermicomposting Research	417
Operation of the Process: How Vermicomposting Works	417

Timing of the Vermicomposting Process and Longevity of Vermicomposts	418
Effects of Vermicomposts on Plant Growth	418
Vermicomposts as Suppressors of Plant Diseases and Plant-Parasitic Nematodes.....	420
References	421

INTRODUCTION

The importance of biological processes in the management and recycling of organic wastes has been widely recognized; this chapter deals with vermicomposting, which is one of the most efficient methods for converting solid organic materials into environmentally friendly, useful, and valuable products for crop production. Vermicomposting is an accelerated process of biooxidation and stabilization of organic wastes that involves interactions between earthworms and microorganisms. Although Darwin (1881) already drew attention to the great importance of earthworms in the breakdown of organic matter from dead plants and the release of nutrients from them, it was necessary to wait almost 100 years until this concept was taken seriously as a technology or even a field of scientific knowledge. After 2 decades of research and technical development on vermicomposting, it is still necessary to depend on a series of fundamental aspects to understand how the process works.

Certain species of earthworms, the main actors in the vermicomposting process, are described briefly in terms of biology and ecology, showing how these animals can be important organic waste decomposers to produce useful materials. The different earthworm species suitable for vermicomposting organic wastes have quite different requirements for optimal development, growth, and productivity. In this chapter, the life cycles of these species and the general requirements of ideal vermicomposting species of earthworms are first reviewed.

Vermicomposting is a complex biological and ecological process; to illustrate some of the important physical, chemical, and biological actions and transformations occurring during it, a case study is presented. Although earthworms are critical in the process of vermicomposting, complex interactions among the organic matter, microorganisms, earthworms, and other soil invertebrates result in the fragmentation, biooxidation, and stabilization of the organic matter. As an example, some of the interactions between earthworms and nematodes are presented. Finally, some comments are made on the applications of vermicomposting to plant growth, and some new perspectives on vermicomposting research are discussed.

WHAT IS VERMICOMPOSTING?

The disposal of organic wastes from domestic, agricultural, and industrial sources into landfills and other outlets has caused increasing environmental and economic problems, and many different technologies to address this problem have been developed and tested. The growth of earthworms in organic wastes has been termed *vermiculture*, and the managed processing of organic wastes by earthworms to produce casts is termed *vermicomposting*. Vermicomposting, which involves the breakdown of organic wastes through earthworm activity, has been successful in processing sewage sludge and solids from wastewater (Neuhauser et al. 1988; Domínguez et al. 2000); materials from breweries (Butt 1993); paper wastes (Butt 1993; Elvira et al. 1995, 1997); urban residues, food wastes, and animal wastes (Allevi et al. 1987; Edwards 1988; Elvira et al. 1996a, 1997; Domínguez and Edwards 1997; Atiyeh et al. 2000a); as well as horticultural residues from processed potatoes, dead plants, and the mushroom industry (Edwards 1988).

Vermicomposting is a decomposition process involving interactions between earthworms and microorganisms. Although the microorganisms are responsible for the biochemical degradation of the organic matter, earthworms are the crucial drivers of the process by fragmenting and conditioning the substrate, increasing surface area for microbiological activity, and altering its biological

activity dramatically. Earthworms act as mechanical blenders, and by comminuting the organic matter, they modify its biological, physical, and chemical status, gradually reducing its C:N ratio, increasing the surface area exposed to microorganisms, and making it much more favorable for microbial activity and further decomposition. During passage of organic matter through the earthworm gut, the fragments and bacteria-rich excrements are moved, thereby homogenizing the organic material.

Vermicompost, which is the end product, is a stabilized, finely divided peatlike material with a low C:N ratio and 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, which reflect greatly enhanced plant availability of nutrients, particularly ammonium radicals and nitrates.

EARTHWORMS

Earthworms can be defined as segmented and bilaterally symmetrical invertebrates 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, and with 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, after which each of the mated individuals can produce cocoons (oothecae) containing between 1 and 20 fertilized ova (although parthenogenesis is also possible). The resistant cocoons, which can survive many years, are tiny and roughly lemon shaped with specific characteristics. 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 favorable conditions, many species can reach sexual maturity within weeks after emergence, although some species that live mainly in soil take longer. Mature individuals can be distinguished easily by the presence of the clitellum, which is a pale or dark-colored swollen band located behind the genital pores. After fertilization, the clitellum secretes the fibrous cocoon, and the clitellar gland cells produce a nutritive albuminous fluid that fills the cocoon. The earthworms can continue to grow in size after completing their sexual development but never add further segments.

The number of earthworm species is enormous; according to Reynolds (1994), there are as many as 7254 species in the Oligochaeta, of which about half (3627) are terrestrial earthworms, with an average annual description of about 68 new species. For most earthworm species, the original genus and species description is the only information available, and for many species, little or nothing is known of their life cycles, distribution, ecology, and the like.

Through feeding, burrowing, and casting, earthworms modify the physical, chemical, and biological properties of the organic matter. Physical properties in soils and wastes processed by earthworms include improved aggregation, stability, and porosity; soil biological and chemical properties that may be 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 the soil pH, 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).

EARTHWORM LIFE HISTORIES

Earthworms, as all organisms, have to distribute the energy obtained in feeding to two main compartments: the reproductive compartment and the somatic compartment. This assignment of resources to either growth or reproduction can be modified according to evolutionary answers to

different environmental factors. These include the availability and the quality of food as well as physical and chemical factors that can affect the earthworms directly or indirectly, modifying the availability of food and other biotic factors like competition. Finally, life histories depend on the different components of the life cycle of each earthworm species.

Different species of earthworms have quite different life histories, behaviors, and environmental requirements occupying different ecological niches. They have been formally classified into three major ecological categories based primarily on their feeding and burrowing strategies (Bouché 1977): epigeic, endogeic, and anecic.

Epigeic 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 most of their activities and effects are limited primarily to the upper few centimeters of the soil-litter interface. They are essentially "litter transformers." They are typically small, 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 in this category can be found aboveground 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, epigeic species are difficult to find, despite their great potential for rapid reproduction. This group of epigeic species includes *Lumbricus rubellus*, *Eisenia fetida*, *Eisenia andrei*, *Dendrobaena rubida*, *Eudrilus eugeniae*, *Perionyx excavatus*, and *Eiseniella tetraedra*.

Endogeic 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 that fill with cast material as they move through the organic-mineral layer of the soil. Earthworms of this type can burrow deep into soils, and unlike r-selected epigeic species of earthworms, they are k-selected species (Satchell 1980; Lavelle 1983) that require a much longer time to achieve their maximum weight and appear to be more tolerant of periods of starvation than are epigeic species (Lakhani and Satchell 1970). These species are apparently of no major importance in litter incorporation and decomposition because they feed on subsurface soil material; they are important in other soil formation processes, including root decomposition, soil mixing, and aeration. Species such as *Allolobophora caliginosa*, *Aporrectodea rosea*, and *Octolasion cyaneum* are included in this endogeic group of species.

Anecic earthworm species live in more or less permanent vertical burrow systems that may extend several meters into the soil profile. The permanent burrows of anecic earthworms create a microclimatic gradient, and the earthworms can be found at either shallow levels or deep in their burrows, depending on the prevailing soil environmental 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 also may create heaps of cast material termed *middens* at the burrow entrance; these consist of a mixture of cast, soil, and partially incorporated surface litter. Characteristically, these earthworms are large in size as adults and dark in color anteriorly and dorsally; their reproduction rates are relatively slow. Anecic species of earthworms, intermediate on the r-k scale (Satchell 1980; Lavelle 1983; Lavelle and Barois 1988), 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 anecic group of earthworms.

EARTHWORM SPECIES SUITABLE FOR VERMICOMPOSTING

Looking at this general ecological grouping, it is obvious that only epigeic species can be expected to be suitable for vermiculture and vermicomposting. Moreover, to consider a species suitable for

use in vermicomposting, it should possess certain specific biological and ecological characteristics, that is, an ability to colonize organic wastes naturally; high rates of organic matter consumption, digestion, and assimilation; ability to tolerate a wide range of environmental factors; high reproductive rates by producing large numbers of cocoons, which should not have a long hatching time, and growth and maturation rates from hatchlings to adult individuals should be rapid; and they should be strong, resistant and survive handling. Not too many species of earthworms possess all these characteristics.

TEMPERATE SPECIES

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

The closely related *E. fetida* and *E. andrei* species are the ones most commonly used for the management of organic wastes by vermicomposting. There are several reasons why these two species are preferred: They are peregrine and ubiquitous with a worldwide distribution, and many organic wastes become naturally colonized by them; they have good temperature tolerance and can live in organic wastes with a range of moisture contents. They are resilient earthworms and can be handled readily; in mixed cultures with other species, they 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, have 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; Domínguez et al. 2000).

Under optimal conditions, their life cycles, from freshly deposited cocoon through sexually mature clitellate earthworm 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 between 0.35 and 1.3 per day. The hatching viability is 72 to 82%, and the incubation period ranges from 18 to 26 days. The number of young earthworms hatching from each viable cocoon varies from 2.5 to 3.8 depending on temperature. Maximum life expectancy is 4.5 to 5 years, but the average life survival was 594 days at 28°C and 589 days at 18°C, although under natural conditions it may be considerably less than these figures because they have so many predators and parasites in the wild (Edwards and Bohlen 1996).

Dendrobaena rubida (Savigny, 1826)

Dendrobaena rubida is a temperate species of earthworm with a clear preference for organic soils, and it inhabits substrates such as decaying rooting wood and straw, pine litter, compost, and peat and is found 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. 1996b), this species is not widely used in vermicomposting systems. *Dendrobaena rubida* can complete its life cycle in 75 days, and its rapid maturation and high reproductive rate could make it a suitable species for vermicomposting. Compared with other vermicomposting species, *D. rubida* grows relatively slowly, although it reaches sexual maturity relatively quickly (54 days after hatching). Cluzeau and Fayolle (1989) reported that it was sexually mature after 44 ± 10 days. We found that the net reproductive rate for *D. rubida* was 2.06 hatchlings per mature earthworm⁻¹ week⁻¹ (Elvira et al. 1996b), although cocoon production rates by *D. rubida* reported in the literature of 3.22 cocoons week⁻¹ (Cluzeau and Fayolle 1989) are usually higher than those we reported (2.31 cocoons week⁻¹; Bengtsson et al. 1986). Gates (1972) reported that only one earthworm emerged from 75% of the cocoons of *D. rubida*, with 2

to 4 hatchlings emerging from the remaining cocoons. According to Cluzeau and Fayolle (1989), one of the factors that contributes to the high fertility rate of *D. rubida* is because its reproduction may be facultatively biparental, amphimictic, or uniparental, either by parthenogenesis (Omodeo 1952) or by self-fertilization (André and Davant 1972).

Dendrobaena veneta (Rosa, 1886)

Dendrobaena veneta is a large species of earthworm with considerable potential for use in vermiculture that can also survive in soil (Satchell 1983). Although it is not very prolific and does not grow very rapidly, it is used by a number of vermiculturalists (Edwards 1988; Viljoen et al. 1991). Of the species that have been considered for vermiculture, it is probably one of the least suitable species for use in organic waste processing or vermicomposting, although it may have some potential for protein production systems and for breeding for soil improvement.

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

Lumbricus rubellus (Hoffmeister, 1843)

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

Lumbricus rubellus has a relatively long life cycle (120 to 170 days) with a slow growth rate and a long maturation time (74 to 91 days) (Cluzeau and Fayolle 1989; Elvira et al. 1996b). We estimated the net reproductive rate to be 0.35 hatchlings earthworm⁻¹ week⁻¹ because of the low cocoon production rate (0.54 cocoons week⁻¹), and only one hatchling emerged from each cocoon (Elvira et al. 1996b). Other researchers have recorded higher cocoon production rates for this species, ranging from 0.49 (Cluzeau and Fayolle 1989) to 1.75 cocoons week⁻¹ (Evans and Guild 1948).

Its low maturation and reproductive rates suggest that it is not an ideal earthworm species for vermicomposting, although its size, vigor, and ability to survive in soils 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)

The *E. eugeniae* species of earthworm belongs to the Eudrilidae; it is a native African species that lives in both soils and organic wastes but has been bred extensively in the United States, Canada, and elsewhere for the fish-bait market, where it is commonly called the African night crawler. It is a large, robust earthworm that grows extremely rapidly, and it is relatively prolific when cultured. Under optimum conditions, it could be considered an ideal species for animal feed protein production. Its main disadvantages are a relatively narrow temperature tolerance and some sensitivity to handling. *Eudrilus eugeniae* can live in soils and has high reproduction rates (Bano and Kale 1988;

Edwards 1988); it is capable of decomposing large quantities of organic wastes rapidly and incorporating them into the topsoil (Neuhauser et al. 1979, 1988; Edwards 1988; Kale and Bano 1988). The life cycle of *E. eugeniae* ranges from 50 to 70 days, and its life span can be 1 to 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 as *E. fetida* and *P. excavatus*, it seems more sensitive to disturbance and handling and may occasionally migrate from breeding beds. However, it has been grown commercially for fish bait for a long time in the United States, which is evidence that 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) (see Chapter 19, this volume).

Perionyx excavatus Perrier, 1872

Perionyx excavatus is an earthworm belonging to the Megascolecidae, commonly found over a large area of tropical Asia (Stephenson 1930; Gates 1972), although it has also been transported to Europe and North America. This is an epigeic species that lives solely in organic wastes. High moisture contents and adequate amounts of suitable organic material are required for populations to become fully established and to process organic wastes efficiently. The life cycle of *P. excavatus* takes 40 to 71 days from hatching to maturity. This species prefers high temperatures and may die at temperatures below 5°C. This is a prolific species that, with about 90% hatching rate and 1.1 hatchlings per cocoon, has a net reproductive rate of nearly 20 cocoons week⁻¹ (Edwards and Bohlen 1996; Edwards et al. 1998).

Pheretima elongata (Perrier, 1872)

Pheretima elongata is a megascolecid earthworm species that 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 it had a commercially viable processing facility for the "vermistabilization" of 8 tons of organic solid waste day⁻¹. These workers developed a "vermifilter" (packed with vermicompost and live earthworms) that produced reusable water from sewage sludge, manure slurries, and organic wastewaters from food processing (Edwards and Bohlen 1996). *Pheretima elongata* appears to be restricted to tropical regions and may not survive severe winters such as those in temperate regions.

Table 20.1 summarizes some aspects of the biology of these vermicomposting earthworm species. A comparison of the duration of the life cycles and the reproduction potential of the earthworm species suitable for vermicomposting is presented in Figure 20.1.

INFLUENCE OF ENVIRONMENTAL FACTORS ON SURVIVAL AND GROWTH OF EARTHWORMS

Cocoon production, rates of development, and growth of earthworms are all affected critically by environmental conditions. Species of earthworms that can be used successfully 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 demonstrated clearly that these earthworm species 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 favorable chemical and environmental conditions. If divergence from these limits is great, the earthworms may move to more

TABLE 20.1
Comparison of Some Aspects of the Biology of the Earthworm Vermicomposting Species

	<i>Eisenia fetida</i>	<i>Eisenia andrei</i>	<i>Dendrobaena rubida</i>	<i>Dendrobaena veneta</i>	<i>Lumbricus rubellus</i>	<i>Drawida nepalensis</i>	<i>Eudrilus eugeniae</i>	<i>Perionyx excavatus</i>
Color	Brown and buff bands	Red	Reddish purple	Reddish and purple bands	Reddish brown	?	Reddish brown	Reddish brown
Size of adult worms	4 to 8 mm × 50 to 100 mm	4 to 8 × 50 to 100 mm	3 to 4 × 35 to 60 mm	5 to 7 × 50 to 80 mm	4 × 70 to 150 mm	?	5 to 7 × 80 to 190 mm	4 to 5 × 45 to 70 mm
Mean weight of adults	0.55 g	0.55 g	0.25 g	0.92 g	0.80 g	0.82 g	2.7–3.5 g	0.5–0.6 g
Time to maturity (days)	28–30	21–28	54	65	74–91	34–42	40–49	28–42
Number of cocoons day ⁻¹	0.35–0.5	0.35–0.5	0.20	0.28	0.07–0.25	0.15	0.42–0.51	1.2–2.7
Mean size of cocoons	4.85 × 2.82 mm	4.86 × 2.64 mm	3.19 × 1.97 mm	3.14 × 1.93 mm	3.50 × 2.46 mm	?	?	?
Incubation time (days)	18–26	18–26	15–40	42.1	35–40	24	12–16	18
Hatching viability (%)	73–80	72	85	20	60–70	75–81	75–84	90
Number of worms cocoon ⁻¹	2.5–3.8	2.5–3.8	1.67	1.10	1	1.93	2–2.7	1–1.1
Self-fertilization	+	+	+	?	–	+	–	?
Life cycle (days)	45–51	45–51	75	100–150	120–170	100–120	50–70	40–50
Limits and optimal <i>T</i>	25°C (0–35°C)	25°C (0–35°C)	?	25°C (15–25°C)	?	?	25°C (16–30°C)	25–37°C
Limits and optimal moisture	80–85% (70–90%)	80–85% (70–90%)	?	75% (65–85%)	?	?	80% (70–85%)	75–85%

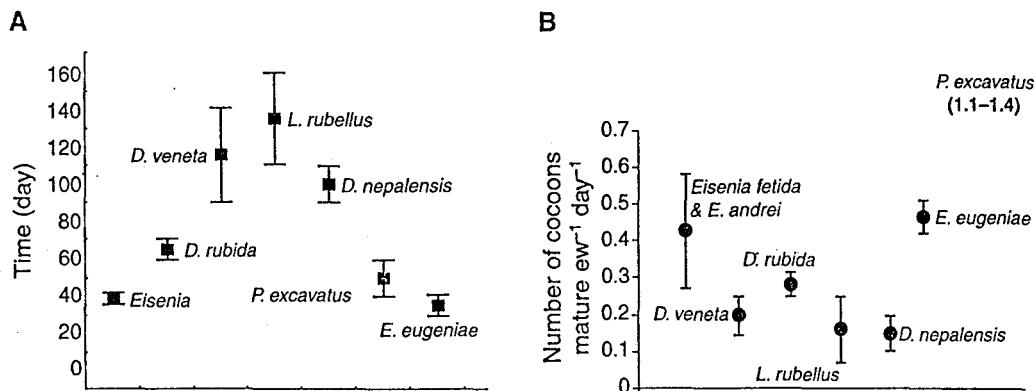


FIGURE 20.1 (A) Length of the life cycle and (B) mean cocoon production of the earthworm species suitable for vermicomposting.

suitable zones in the waste, leave the waste, or die, so that the wastes are processed only slowly. This means that processing under some form of cover is preferable.

TEMPERATURE

Earthworms have 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 a range of preferred temperatures for growth ranging between 15 and 25°C. In their 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 response and tolerance to different temperatures. The optimum temperature for *E. fetida* was 25°C, and its temperature tolerance was between 0 and 35°C. *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 most suitable for growth for all these species.

Temperatures below 10°C generally resulted in reduced or little feeding activity; below 4°C, cocoon production and development of young earthworms ceased completely (Edwards and Bohlen 1996). In extreme temperature 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 for long periods when exposed to freezing conditions.

The unfavorable effect of high temperatures (above 30°C) on most species of earthworms is not entirely a direct effect because 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 survival of earthworms.

MOISTURE CONTENT

There are strong relationships between the moisture contents in organic wastes and the growth rate of earthworms. In vermicomposting systems, the optimum range of moisture contents for most species has been reported to be between 50 and 90% (Edwards 1998). *Eisenia fetida* can survive in moisture ranges between 50 and 90% (Sims and Gerard 1985; Edwards 1988) 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. By comparison, *E. andrei* cultured in pig manure grew and matured best between 65 and 90% moisture content, with 85% the optimum (Domínguez and Edwards 1997). According to Reinecke and Venter (1985), it seems likely that lowering of the growth rate because of low moisture conditions can also retard sexual development, so earthworms of the same age could develop clitella at different times under different moisture conditions.

PH

Most species of epigeic earthworms are relatively tolerant to pH, but when given a choice in the pH gradient, they moved toward the more acid material, with a pH preference of 5.0. 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. Lime is commonly added to vermicomposts.

AERATION

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

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 quantities of inorganic salts. Both ammonia and inorganic salts have very sharp cutoff points between toxic and nontoxic (i.e., <1 mg/g of ammonia and <0.5% salts) (Edwards 1988). However, organic wastes containing large amounts of ammonia can become acceptable after its removal by a period of composting.

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 preconditioned to make them suitable for vermicomposting.

Earthworm population density is known to affect the rates of earthworm growth and reproduction. Even when the physical-chemical characteristics of the wastes are ideal for vermicomposting, problems can develop because of overcrowding. Reinecke and Viljoen (1990), in studies with *E. fetida* reared in cow manure, and Domínguez and Edwards (1997), who studied 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 body weight, although the total weight of earthworm biomass produced per unit of waste was greater in the crowded dishes. Maturation rates were also affected by the population density; earthworms of the same age developed a clitellum at different times in cultures with different earthworm stocking rates; usually, it was later in dense populations.

When the environmental conditions are maintained within adequate ranges, a maximum yield of about 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 present initially (Hartenstein 1983; Edwards 1988). Although this conclusion was based on laboratory experiments, a similar earthworm yield can be expected from field systems that are managed well.

It is likely that ingestion of organic waste by earthworms stops when a critical level of humified material appears, rich in free-radical and noningestible content, despite the remaining abundance of oxidizable carbon (Hartenstein 1983; Hartenstein and Neuhauser 1985). This might account for the relatively low biomass of earthworms in tropical soils despite the high availability of organic carbon from vegetation and the rapid rates of soil and organic matter turnover. However, this needs further investigation.

EFFECTS OF DIET ON THE GROWTH AND REPRODUCTION OF EARTHWORMS

Earthworms obtain their energy from the organic matter on which they feed, and their effects on the characteristics of this organic matter will depend on the quality of the resource and on the earthworm species. Earthworms fragment organic wastes with a grinding gizzard, aided by grit and sand, and this increases the surface area of the organic matter and promotes very high microbial activity. Moreover, the earthworms use the microorganisms for a nutrient source rather than the organic matter.

Vermicomposts can be produced from almost any kind 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 can 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 *E. andrei*, we found that the maximum earthworm weights achieved, and the highest growth rates, occurred in the mixture with food waste added (755 ± 18 mg and 18.6 ± 0.6 mg day⁻¹, respectively), whereas the smallest earthworm sizes and the lowest growth rate occurred in a 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 with the reproduction in the control with sewage sludge alone (0.05 ± 0.01 cocoons earthworm⁻¹ week⁻¹) (Figure 20.2) (Domínguez et al. 2000).

ECOLOGY OF VERMICOMPOSTING: A CASE STUDY

An experiment in our laboratory at the University of Vigo in Spain studied a vermicomposting system with different mixtures of pig manure slurries and agro-forestry by-products. This research project evaluated the characteristics of the vermicomposts produced after different processing times. The vermicomposting boxes were sampled monthly during a year; numbers and total weights of earthworms and cocoons were recorded, and several physical and chemical parameters were measured.

In most of the vermicomposting systems, an initial 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 increased gradually to final values that were considerably greater than the initial ones. One possible cause is that, in microcosm experiments, earthworms are unable to find suitable ecological habitats and may suffer an initial stress in activity and feeding. As a consequence, the effects of earthworms on the decomposition of the organic matter were much greater during the final stages of the process when the earthworm populations were more conditioned and

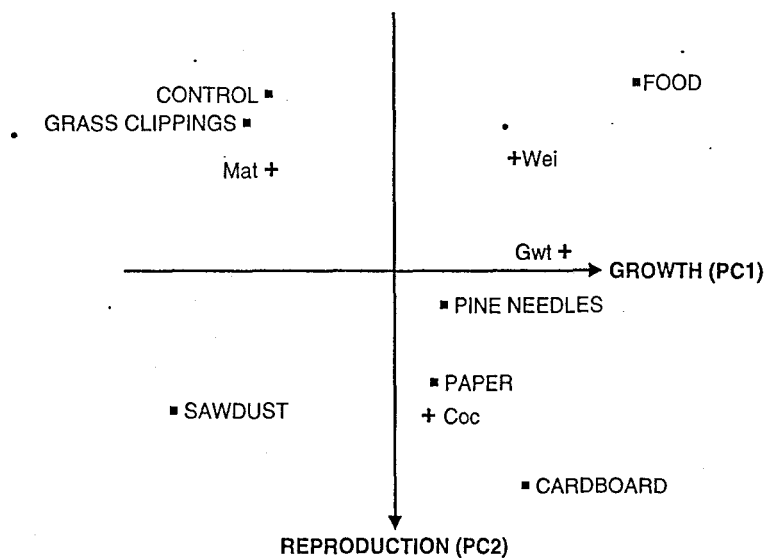


FIGURE 20.2 Effect of different diet treatments in the plan defined by factorial axes representing growth and reproduction of the earthworm *Eisenia andrei*. Mat, sexual maturity; Wei, earthworm weight; Gwt, earthworm growth; Coc, cocoon production; PC1 represents 46.5% of total inertia, and PC2 represents 36.87%.

active. Transformations of the organic wastes after 2 months during this effective vermicomposting period are summarized in Figure 20.3.

pH DURING VERMICOMPOSTING

The pH of the pig slurry used in our vermicomposting experiments ranged from 8.2 to 8.7. The vermicompost obtained after 2 months was slightly acidic, with similar pH values to the parent waste without earthworms (control), proving that earthworms did not affect the pH values to any great extent (Figure 20.3A). The effects of earthworms on pH of wastes 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.

CARBON MINERALIZATION DURING VERMICOMPOSTING

Similar to other invertebrates in the organic matter decomposer community, earthworms can assimilate carbon best from the more recently deposited organic matter fractions, consisting mainly of easily degradable substances. 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 (Figure 20.3B). Although earthworms consume and process large amounts of organic matter, their contributions to the total heterotrophic respiration is quite low because of their poor assimilation efficiency; only when there are large active earthworm populations, as in vermicomposting systems, can they contribute appreciably to the total heterotrophic respiration.

NITROGEN TRANSFORMATIONS DURING VERMICOMPOSTING

Earthworms had a great impact on the nitrogen transformations in the pig manure by enhancing nitrogen mineralization, so that most mineral nitrogen was retained as nitrates. The net total nitrogen and the different nitrogen fractions decreased during vermicomposting, and important reductions in organic nitrogen content and a high nitrification rate were noted (Figure 20.3C). This implies

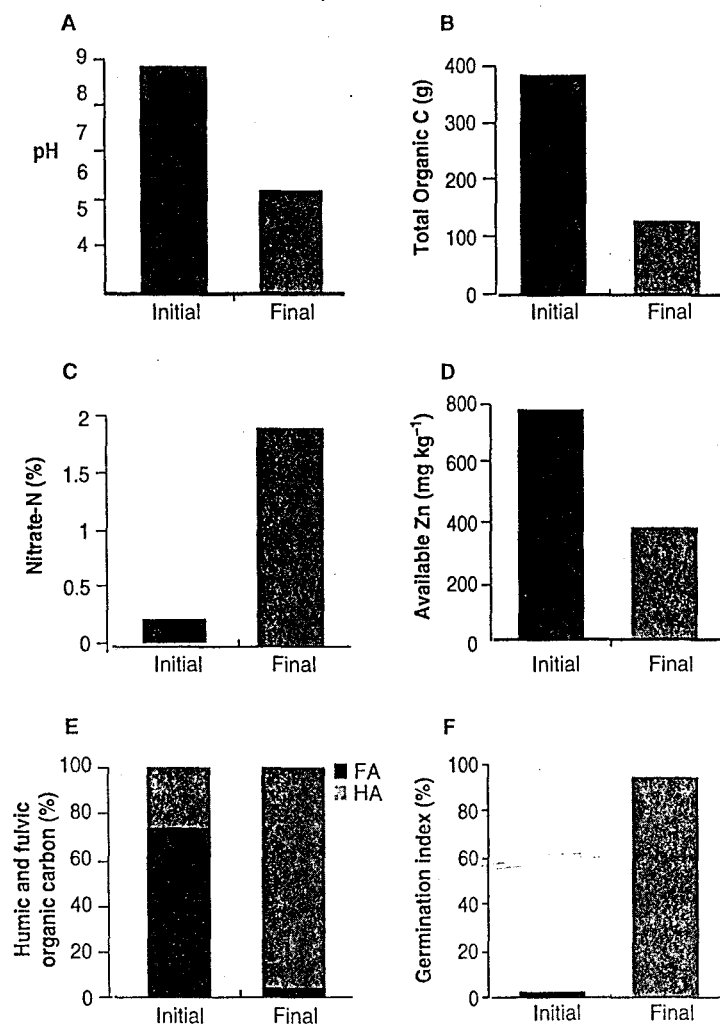


FIGURE 20.3 Changes in some properties of pig manure after 2 months of effective vermicomposting with the earthworm *Eisenia andrei*: (A) effect of the vermicomposting process on pH; (B) carbon mineralization during vermicomposting; (C) nitrification during vermicomposting; (D) heavy metal availability (extractable with ammonium bicarbonate diethylene triamine pentaacetic acid (AB-DTPA) after vermicomposting; (E) humification during vermicomposting; (F) germination index of *Lepidium sativum* in vermicompost from pig manure.

that earthworms (*E. andrei* in this case) provided conditions in the manure that favored nitrification, resulting in the rapid conversion of ammonium into nitrates. Similar results have been reported by Hand et al. (1988), who found that *E. fetida* in cow slurry increased the nitrate concentration of the substrate (Atiyeh et al. 2000a) (see Chapter 18, this volume).

VERMICOMPOSTING AND HEAVY METAL AVAILABILITY

It is important to follow changes in the total and available contents of heavy metals in the organic wastes during the vermicomposting process because they may cause problems in some animal manures, sewage sludges, and industrial organic wastes. In our experiments, the total amounts of heavy metals increased (by between 25 and 30%) as a consequence of the carbon losses by mineralization during vermicomposting, and the amounts of bioavailable heavy metals tended to

decrease with a decrease because of chemical binding of between 35 and 55% in bioavailable metals in 2 months (Figure 20.3D). Similar results have been reported in other studies of both composting and vermicomposting, and this implies a lower availability of heavy metals for plants from composts or vermicomposts. During vermicomposting, heavy metals tend to form complex aggregates with the humic acids and the most polymerized organic fractions.

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 humuslike material and become stabilized. In our 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 (Figure 20.3E), so, clearly, earthworm activity accelerates the humification of organic matter. Moreover, during vermicomposting, the amounts of humic materials increased from 40 to 60%, which was more than the values obtained in a composting process using the same waste materials. Humification processes are accelerated and 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 and turnover of the organic matter through earthworm movement and feeding.

STABILITY OF ORGANIC WASTES AND MATURITY OF THE VERMICOMPOSTS

The stability and maturity of organic wastes, which imply 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 our example, the germination percentages of *Lepidium sativum* indicated that the initial organic wastes were toxic to the plants, probably because of their high ammonium content, but this toxicity was removed gradually during 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 on germination (Figure 20.3F).

VERMICOMPOSTING AND HUMAN PATHOGEN DESTRUCTION

Preliminary research in our laboratory, and in the Soil Ecology Laboratory at The Ohio State University, has shown that vermicomposting involves a great reduction in populations of human pathogenic microorganisms, as in composting. It is generally accepted that the 72 hours of the thermophilic stage of the composting process eliminate pathogenic organisms, but these studies have shown that human pathogens also do not survive vermicomposting. After 60 days of vermicomposting, the amounts of fecal coliform bacteria in biosolids dropped from 39,000 MPN (most probable number)/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), also for fecal coliforms and *Salmonella* sp. and for enteric virus and helminth ova, and other authors (see Chapter 18 this volume).

SOIL FOOD WEBS IN THE VERMICOMPOSTING SYSTEM

Earthworms participate in soil functions through the *drilosphere*, which is defined as the space of interactions among earthworms, soil or waste physical structure, and the whole microbial and invertebrate communities (Lavelle et al. 1998). As a result of organic matter digestion processes by earthworms and the creation of soil structures (see Chapter 11 this volume), the overall composition, structure, and the relative importance of the drilosphere is clearly determined by environmental conditions, soil characteristics, and the quality and amounts of the organic matter inputs.

In vermicomposting, complex interactions occurring between the organic matter, microorganisms, earthworms, and other soil invertebrates result in a rapid biooxidation and stabilization of the organic matter. Most vermicomposting systems sustain complex food webs and at the same time modify the chemical forms of several nutrient elements into longer-lived organic compounds important for nutrient dynamics (Domínguez et al. 1997).

Although populations of some sensitive organisms may be reduced drastically or eliminated during vermicomposting, the substrate maintains an overall increased active community of decomposer organisms, which in addition to earthworms, includes enchytraeids, nematodes, springtails, mites, protozoa, and very large populations of microorganisms.

The complex food webs in the vermicomposting systems can be represented as 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 modes of operation. At the microbial microscale, there are basically bacteria (unable to move long 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 level but gradually increasing in size and spatial influence, the micro-food web includes microinvertebrates, such as nematodes, protozoa, and rotifers, which feed primarily on microorganisms. At the mesoscale level, there are larger organisms, such as enchytraeids 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 level, there is the main component of the vermicomposting system, the earthworms, which feed on and disperse microorganisms. As they feed on decaying organic matter, earthworm burrowing and tunneling activities aerate the substrate and enable water, nutrients, and oxygen to filter through it; their feeding activities increase the surface area of organic matter for microorganisms to act on. As some decomposers die, more food is added to the food web for other decomposers.

As organic matter passes through the earthworm's gizzard, it is finely ground before digestion. Then, digestive microorganisms, and possibly enzymes and other fermenting substances, continue the breakdown process. The organic matter passes out of the earthworm's body in the form of casts, or *vermicomposts*, which are rich in nutrients and microorganisms and are of fine quality and structure.

Earthworms can exert various influences on soil microorganisms and invertebrate populations directly or indirectly via comminution, burrowing, casting, grazing, and dispersal. Not only does the physicochemical and biological status of the organic matter and soil change for the better during the course of these activities, but the characteristics of the drilosphere may also be altered dramatically (see reviews by Brown 1995 and Doube and Brown 1998; see Chapter 12, this volume). 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 organic matter degradation through its interactions with soil microorganisms.

Because vermicomposting systems teem with an enormous biodiversity 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 bedding plant container media and for soils that have been intensively chemically managed or have become impoverished. As the understanding of soil ecology increases, the determination and analysis of the structure of decomposer food webs in organic amendments may become an important predictive tool in evaluating their potential qualities and value.

An interesting example of such interactions in the food web is the effect of earthworms (*E. andrei*) on nematode populations during vermicomposting (Domínguez et al. 2003) (Figure 20.4).

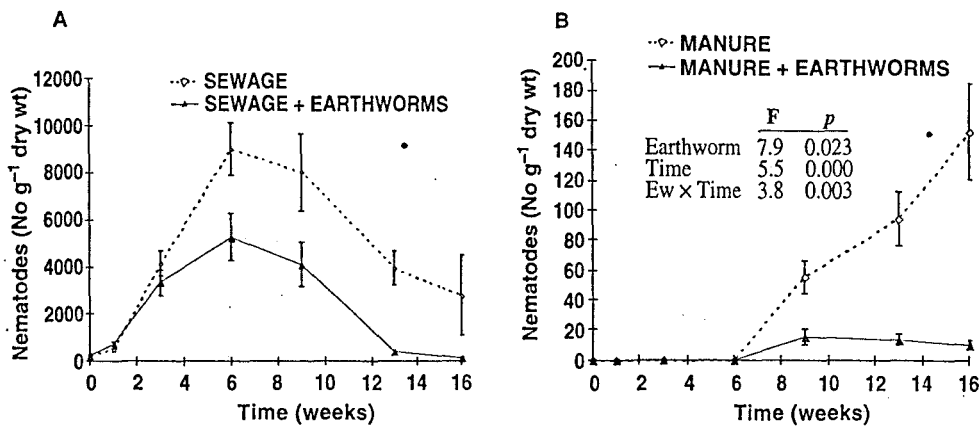


FIGURE 20.4 (A) Bacterivore and (B) fungivore nematode abundance (mean \pm SE) in presence and absence of the earthworm *Eisenia andrei* during vermicomposting of cow manure and sewage sludge. (From Domínguez et al. 2003.)

The density of bacterivorous nematodes increased with time during the first 6 weeks in sewage sludge in the presence or the absence of earthworms; after week 6, the density of bacterivorous nematodes started to decline independently of the presence of *E. andrei* in the culture boxes. However, it was remarkable that the number of bacterivorous nematodes was always considerably lower in the presence of earthworms, and that these differences were statistically significant after 10 weeks (Figure 20.4A). Fungivorous nematodes did not appear in the sewage sludge during the 16 weeks of the experiment, but fungivorous nematodes appeared in cow manure after 6 weeks; their numbers increased strongly in the absence of earthworms and remained constantly low in the presence of *E. andrei*. After 16 weeks, the density of fungivorous nematodes was 150 ± 30 nematodes g⁻¹ dry weight in the treatment with no earthworms and only 10 ± 2 nematodes g⁻¹ dry weight in the treatment with earthworms (Figure 20.4B).

APPLICATIONS OF VERMICOMPOSTING

From the point of view of its commercial development and application, vermicomposting and any other biological treatment of organic wastes can be considered two-step processes. The first step is to convert the organic wastes into nontoxic products, eliminating or reducing human pathogen content and the concentrations of heavy metals and organic pollutants. A second step takes the process further by converting the new stable product into a valuable organic soil amendment with greatly increased microbial activities and by the humification of the organic material, which enhances the presence of plant growth promoters (Atiyeh et al. 2002b) (see Chapter 18 this volume) (Figure 20.5). So, a decision must be made, and the main criterion for this is the quality of the organic waste. If the residue is "bad," then it may just be stabilized; if it is "good," then there is the possibility of transforming it into a valuable organic soil amendment. A bad waste is, for example, sewage sludge because of its heterogeneous and highly variable composition and high concentration of human pathogens and organic and inorganic contaminants. In this case, the objective of the treatment should be to rapidly stabilize the material, and probably regular composting is a better solution than vermicomposting. A good waste, for example, is most animal wastes, wine residues, food wastes, or milk industry sludges. They are good because they have no pollutants, have a homogeneous composition, and have a good balance of nutrients; in this case, the objective could be to obtain a good organic soil amendment, and vermicomposting is probably the better choice (Figure 20.5).

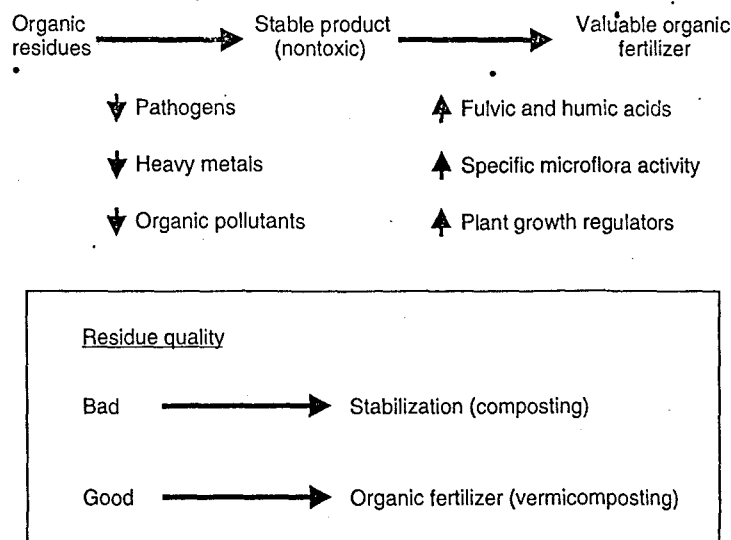


FIGURE 20.5 Vermicomposting and any other biological treatment of organic wastes can be considered as two-step processes.

NEW PERSPECTIVES IN VERMICOMPOSTING RESEARCH

Although an interest in vermicomposting research and technology has been increasing at a rapid rate and the body of knowledge now available is quite large, there are still many questions to be investigated. The topics of some of these questions are discussed here: the method of operation, the management of the process, the effect of the earthworms, the timing of the process or the resident time of the wastes to be converted into real biological soil amendments, the reason why vermicompost promotes plant growth, or the "mean life" or "expiration date" of these vermicomposts.

OPERATION OF THE PROCESS: HOW VERMICOMPOSTING WORKS

The classical approach in all research projects on vermicomposting and in the case study presented in this chapter consists of adding earthworms into organic residues and obtaining vermicompost (see Figure 20.6A). With a reductionist approach such as this, it is difficult to know how the vermicomposting system works and the role of the earthworms in the process. Figure 20.6B represents a simplified model of the vermicomposting process; in ways similar to nature, earthworms obtain their energy from the organic matter, and their effects on the waste depend on the quality and quantity of the resource and on the earthworm species used. The vermicomposting process consists basically of two different subprocesses. The first involves the earthworm gut-associated processes (GAPs), which include all the modifications that the organic matter undergo during transit through the intestinal tract, including the transformation of nutrients, modifications and increases in microbial diversity and activity, modifications of microfaunal populations, homogenization, and the processes of digestion, assimilation, and excretion of the wastes. Once the earthworm GAPs end, the resultant casts are exposed to cast-associated processes (CAPs); here, the effects of the earthworms may be only indirect and include aeration of the substrate because of the burrowing activities. Moreover, earthworm casts are subject to an aging process and to the action of microorganisms and microinvertebrates present in the substrate; it is important to note that, during action of the vermicomposting systems, the casts are mixed with materials that were not eaten by the earthworms.

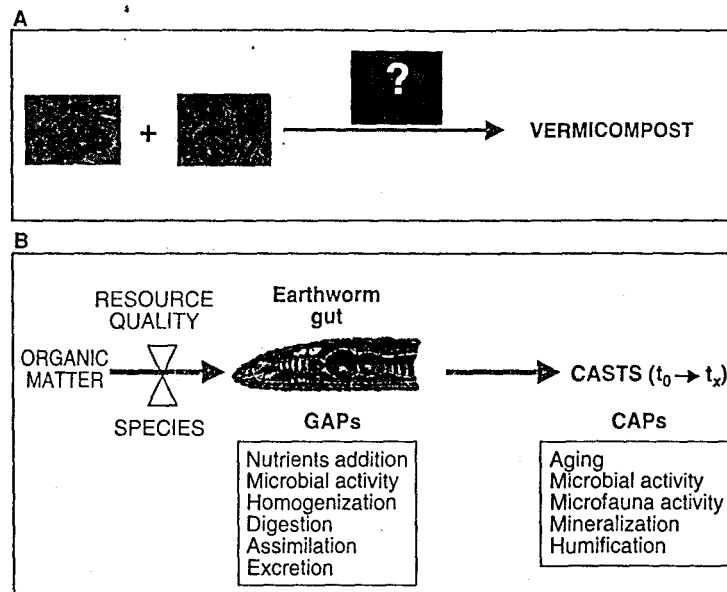


FIGURE 20.6 Different strategies on vermicomposting research: (A) classical approach utilized in most studies; (B) split approach in two different processes, gut-associated processes (GAPs) and cast-associated processes (CAPs).

One example of these two different ways to study the vermicomposting process is given in Figure 20.7. The number of total coliform bacteria remains more or less stabilized in pig manure in the absence of earthworms and decreases sharply in the presence of earthworms (Figure 20.7A); the passage through the earthworm gut (GAP) does not affect human pathogen populations (Figure 20.7B), and the effect of the CAPs on human pathogen numbers after 2 months is quite different in the noningested waste, in the mixture of casts and waste, and in the casts, with these presenting the lowest numbers (Figure 20.7C). Studies of the vermicomposting process through such different compartments can give more detailed information of the biotic and abiotic changes in the organic wastes.

TIMING OF THE VERMICOMPOSTING PROCESS AND LONGEVITY OF VERMICOMPOSTS

Directly related to the explanation above is the timing of the vermicomposting process, such as when the process is completed, and if there is an optimum level of biotic activity in the vermicompost. The first phase, the passage of the organic matter through the earthworm gut (GAP), is rapid, and it is important to determine the magnitude and importance of the biochemical and physical changes during this gut transit. Once the fresh earthworm casts are deposited, then something like a "maturation" process of these casts starts. During this aging, vermicomposts reach an optimum in terms of biological properties that promote plant growth and suppress plant diseases. There are no data about when this optimum is achieved, how it can be determined, and how to determine if this optimum has some kind of longevity or expiration date (Figure 20.8).

EFFECTS OF VERMICOMPOSTS ON PLANT GROWTH

Earthworms have beneficial physical, biological, and chemical effects on soils, and these effects can increase plant growth and crop yields in both natural and agroecosystems (Edwards and Bohlen 1996; Edwards 1998) (see Chapter 18 this volume). These beneficial effects have been attributed to improvements in soil properties and structure (Kahsnitz 1992), to greater availability of mineral

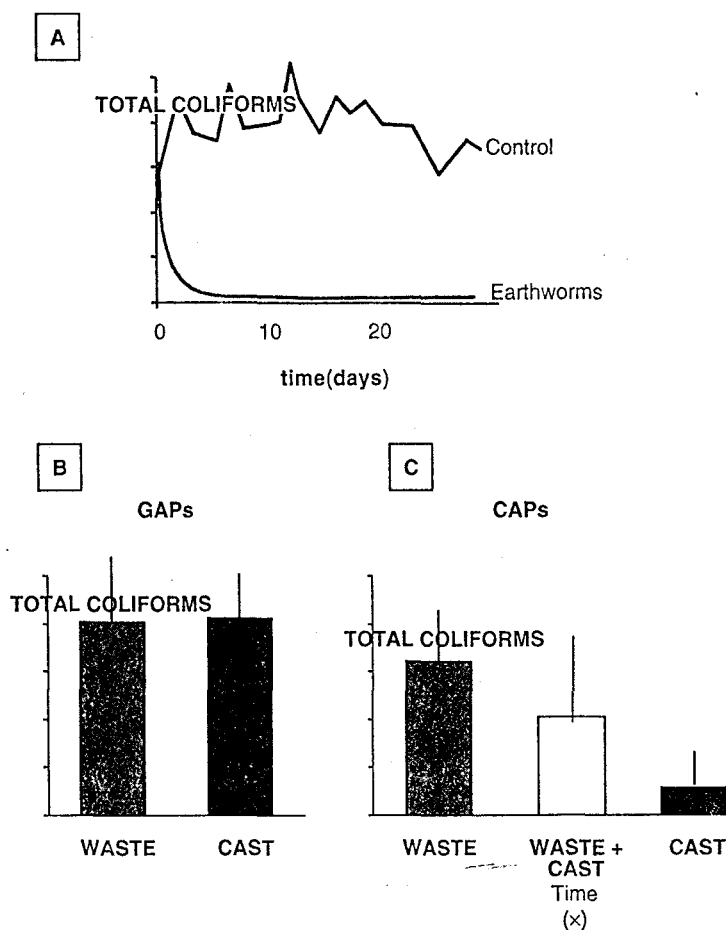


FIGURE 20.7 A case example of different strategies on vermicomposting research: (A) classical approach; split approach in (B) gut-associated processes (GAPs) and (C) cast-associated processes (CAPs).

nutrients to plants (Gilot 1997), to enhancement of mycorrhizal infection, to control of plant parasitic nematode populations, to increased microbial populations, and to biologically active metabolites such as plant growth regulators (Tomati and Galli 1995; Doube et al. 1997) and humates (Atiyeh et al. 2002b).

The effects of vermicomposts on the growth of a variety of crops, including cereals, legumes, vegetables, ornamental and flowering plants, and trees, have been assessed in the greenhouse and to a lesser degree in field crops (Chan and Griffiths 1988; Edwards and Burrows 1988; Wilson and Carlile 1989; Mba 1996; Thankamani et al. 1996; Buckerfield and Webster 1998; Buckerfield et al. 1999; Nethra et al. 1999; Atiyeh et al. 1999, 2000b,c, 2002a,b) (see Chapter 18, this volume). These investigations have demonstrated consistently that vermicomposts have beneficial effects on plant growth independent of nutrient transformations and availability. Whether vermicomposts are used as soil additives or as components of horticultural soilless bedding plant container media, vermicomposts have consistently improved seed germination, enhanced seedling growth and development, and increased plant productivity and yields much more than would be possible from the mere conversion of mineral nutrients into more plant-available forms. The greatest plant growth responses and yields have occurred constantly when vermicomposts constituted a relatively small proportion (10 to 40%) of the total volume of the plant growth medium in which they are incorporated. Usually, greater proportions of vermicomposts substituted in growth media have not increased plant growth as much as smaller proportions (Atiyeh et al. 1999, 2002a,b). This could

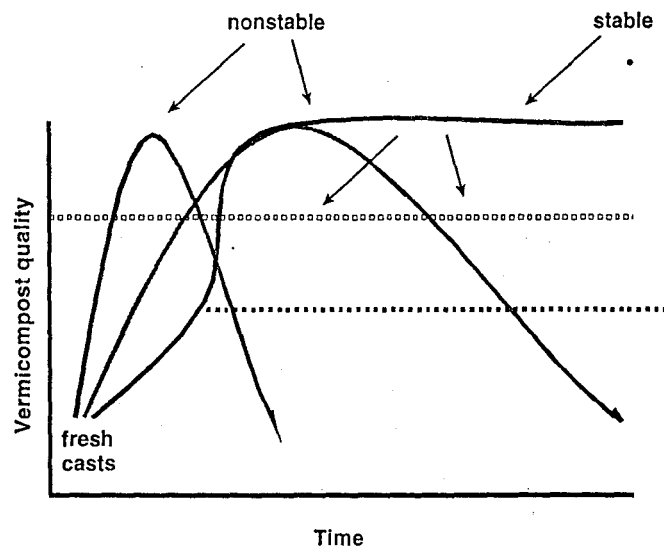


FIGURE 20.8 Timing of the vermicomposting process. There are no data on when a vermicompost can be considered optimum, on how this optimum can be determined, and if this optimum has some kind of "expiration date."

be because of adverse growth factors, such as high levels in 100% vermicomposts, particularly those from animal wastes.

In spite of all this research on the effects of vermicomposts on plant growth, there are still few data in the literature validating possible mechanisms by which vermicomposts produce these growth enhancement effects.

VERMICOMPOSTS AS SUPPRESSORS OF PLANT DISEASES AND PLANT-PARASITIC NEMATODES

Although there are not many studies regarding vermicomposts as suppressors of plant diseases and plant-parasitic nematodes, it has been shown that the incidence of plant diseases can be limited by vermicomposts. Substrates supplemented with vermicompost were suppressive to root rot of tomato caused by *Phytophthora nicotianae* var. *nicotianae*, and dipping cabbage roots in a mixture of clay and vermicompost decreased infection by *Plasmodiophora brassicae* (Szczzech et al. 1993); they also reduced infection of tomato plants by *Fusarium oxysporum* f. sp. *lycopersici* (Szczzech 1999). Vermicompost at a concentration of 40 $\mu\text{g/ml}$ caused a 50% reduction of zoospore formation of *Phytophthora cryptogea*, and amendment of soil extract with 1000 $\mu\text{g ml}^{-1}$ of vermicompost completely inhibited the pathogen sporulation. Peat drenched with vermicompost extracts immediately after planting of gerbera, ivy, carnation, or cyclamen significantly suppressed the spread of diseases. The compound applied at a concentration of 25% caused a decrease of about 50% of propagule numbers of *Fusarium oxysporum* f. sp. *dianthi* in peat naturally infested with the pathogen (Orlikowski 1999). Vermicompost incorporation at a 20% rate reduced the incidence of diseased plants of gerbera (*Gerbera jamesonii* H. Bolus), the area under the disease progress curve, and the disease growth rate of the fungi *Rhizoctonia solani*, *Phytophthora drechsleri*, and *Fusarium oxysporum* (Rodríguez et al. 2000). Chaoui et al. (2002) demonstrated suppression of *Pythium*, *Rhizoctonia*, and *Verticillium* by vermicomposts. Arancon et al. (2002, 2003) demonstrated consistent suppression of plant-parasitic nematode populations by vermicomposts under pepper, tomatoes, strawberries, and grapes in the field.

Clearly, vermicomposts cannot only suppress plant pathogens and plant parasitic nematodes, but they can also promote germination, growth, yields, and fruiting of many plants.

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