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Compendium on Solid Waste Management by Vermicomposting

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August 1980

COMPENDIUM ON SOLID WASTE MANAGEMENT BY VERMICOMPOSTING

by

Camp Dresser & McKee, Inc.
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Project Officer

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FOREWORD

The U.S. Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimonies to the deterioration of our natural environment. The complexity of that environment and the interplay of its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution; it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems to prevent, treat, and manage wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, to preserve and treat public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research and provides a most vital communications link between the researchers and the user community.

This report provides an engineering and scientific assessment of municipal solid waste management by vermicomposting. Vermicomposting is the conversion of waste materials by earthworm consumption to castings which may be used as a soil amendment.

Francis T. Mayo, Director
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ABSTRACT

Vermicomposting -- the conversion of organic matter that occurs as earthworms feed on waste materials -- has been proposed as a method of managing municipal solid wastes. Some species of earthworms (Eisenis foetida and Lumbricus rubellus) can consume wastes and expel the remains as castings. The casting have properties that make them a desirable soil amendment.

Vermicomposting of municipal solid wastes has been attempted only in the last five years and there are presently no full-scale operations. This report assesses the technical and economic feasibility of vermicomposting and is based on several pilot-scale studies conducted by private entrepreneurs.

The assessment is based on examining facilities and costs for a municipal operation serving (1) a community of 50,000 persons and (2) a community of about 500,000 persons. Vermicomposting is compared to three other methods of solid waste management: sanitary landfill, windrow composting, and combustion. Vermicomposting was estimated to cost about $24 to $32 per ton of waste processed. This cost is high compared to most other available methods. Additionally, the market for earthworm castings is not established. Since total process costs, including revenue from sale of products, are central considerations in the selection of a preferred solid waste management option, the typical communities examined in this report have available to them technologies which are more attractive than vermicomposting.

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SECTION 1

EXECUTIVE SUMMARY AND RECOMMENDATIONS

This report provides an engineering and scientific assessment of municipal solid waste management by vermicomposting. The study was carried out as a work effort (WE-1) under Contract No. 68-03-2803, U.S. Environmental Protection Agency, Municipal Environmental Research Laboratory. The investigation combined review of pertinent technical and non-technical (both domestic and foreign) literature, written and telephone contact with representatives of the vermiculture industry and researchers in the field, and visits to Ogden, Utah, where vermicomposting is being pilot tested, and the State University of New York in Syracuse, where research on vermicomposting is being conducted.

Vermicomposting is the conversion of the biodegradable portion of municipal solid wastes by earthworm consumption. Some species of earthworms (Eisenia foetida and Lumbricus rubellus) can consume these wastes and expel the remains as castings. The castings have properties that make them a desirable soil amendment.

Vermicomposting of municipal solid wastes has been attempted only in the last five years. While there are currently no full-scale municipal or private operations, vermicomposting of other wastes (e.g., sludge, dairy manure, and food processing wastes) is being carried out successfully at several installations. This report focuses only on the vermicomposting of municipal solid wastes.

At Ogden, Utah, vermicomposting has been tested on approximately 10 tons of shredded wastes, from which ferrous metals had been removed. The wastes were placed in shallow windrows covering about 800 sq ft, moistened, and allowed to compost for a few weeks. Earthworms were then added at a rate of about 1.5 to 2.0 lb/sq ft. During the next month, additional wastes were added on top of the windrows; in all, the wastes remained in the windrows for about a four-month period, with a calculated area loading rate of approximately four tons of waste per acre per day.

During this time some of the material was converted by the earthworms to castings. A screen was used to separate earthworms from castings and residue, with the intention of using recovered earthworms as stock for any new windrows, using castings as soils amendment, and landfilling the residue. Out of a given weight of municipal solid waste received, approximately one-third is converted to castings.

Based on the results in Ogden, we analyzed the measures required to upgrade and expand the operation to full-scale, and to develop operating parameters and probable costs for the full-scale operation. The full-scale facilities analyzed would process wastes from, respectively, a community of about 50,000 residents, generating 100 tpd of solid waste, and a community of about 500,000, generating 1,200 tpd of solid waste.

The 50,000-person community is intended to be representative of all communities up to that size. Since facilities for smaller communities would require similar equipment -- but without the economies of scale obtained at the 50,000-person level -- it is safe to assume that if vermicomposting were found uneconomical for facilities serving a 50,000-person community, it would be uneconomical also for facilities in an operation of smaller scale. Comparable waste-management alternatives for a community of 50,000 would include landfilling, combustion in modular combustion units (MCUs) with sale of the steam produced in MCU boilers, and windrow composting.

Facilities for vermicomposting in the 50,000-person community would consist of equipment and structures for preprocessing the solid wastes, vermicomposting, and residual disposal. Components of preprocessing would include a receiving area, a primary shredder capable of reducing particle size to a nominal 4 to 6 inches, equipment for magnetic ferrous separation, and storage facilities.

For the facility serving a population of 50,000, costs and land requirements of vermicomposting and comparable processes are as follows:

	Cost per Ton ($)	Area Required for 20-year Project (acres)
Vermicomposting	24 to 32	63
Windrow Composting	24 to 28	61
Modular Combustion Units	15	20
Landfilling	6	112

These costs and area requirements indicate that vermicomposting is far costlier than the land-intensive practice of landfill disposal. Vermicomposting requires considerably more land (including 38 acres of a sanitary landfill) and is more expensive than combustion of solid waste with energy recovery in MCUs. Costs and land area requirements of vermicomposting and windrow composting are very similar. Since availability of land and total process costs are central considerations in selecting among solid-waste management alternatives, the typical community of 50,000 residents has available to it technologies which are more attractive than vermicomposting.

For the community of 500,000 persons, representing a major metropolitan area, it was assumed that vermicomposting techniques would be applied to only 100 tpd of the total 1,200-tpd waste stream. The remainder of the wastes would be processed and burned to produce steam and electricity.

In this case, because the vermicomposting operation would receive shredded wastes with ferrous metals removed, only facilities for vermicomposting and residue disposal would be required.

Vermicomposting a portion of the 1,200-tpd waste steam would be more expensive than other alternatives available to a municipality of 500,000. Production and combustion of RDF, combined with vermicomposting, would cost about $450,000 more annually than production and combustion of RDF alone; the increased cost is due primarily to loss of revenues from sale of steam and electricity.

Vermicomposting shares with other solid-waste management alternatives the structural and operating constraints imposed to avoid contamination of surface waters and groundwater by uncontrolled runoff and leachate, to secure against disease vectors, and to control odors.

Vermicomposting cannot claim an established or projected market for its products -- worms and worm castings. Worms used in vermicomposting do not make ideal baitworms for sportfishing, and this constitutes the sole recognized market for worms. Castings, while apparently a useful soil amendment with attractive aesthetic and handling properties, are produced in quantity by vermiculturists who serve established, but highly limited, speciality markets. Also, any product obtained through vermicomposting of municipal solid waste could potentially be restricted by public-health considerations. Although public health concerns have not been documented, any pathogenic organisms and toxics wastes in the municipal solid waste consumed by the earthworms will be present in the castings. Further research is required in this area, and in the area of vermicomposting of more readily degradable wastes -- such as certain types of agricultural and industrial wastes and municipal wastewater sludges -- that do not require expensive preprocessing before the vermicomposting process is begun.

Municipal solid waste vermicomposting has apparent advantages and disadvantages over other waste management methods. Some of the advantages are:

- Recovery and recycling of the organic fraction of solid waste as earthworm castings.
- Reduced land area requirements for processing and disposal compared to the commonly used sanitary landfill operation.

Some of the major disadvantages are:

- Expensive shredding of wastes required before vermicomposting.
- High capital and operating costs compared to other available methods.

- An unknown market for the earthworm castings.
- Potential public health and environmental concerns in dispersal of castings.

SECTION 2

THE VERMICOMPOSTING PROCESS

PURPOSE OF STUDY

This "Compendium on Solid Waste Management by Vermicomposting" is an engineering and scientific feasibility study of vermicomposting as a means of converting municipal refuse to a usable soils amendment. The report contains:

- o Discussion of the state-of-the-art of vermicomposting of municipal solid waste
- o Engineering analysis of the technical and economic aspects of vermicomposting
- o Recommendations as to the applicability of vermicomposting to present and future solid waste management needs.

Work was carried out as a work effort (WE-1) under Contract No. 68-03-2803, U.S. Environmental Protection Agency (EPA), Office of Research and Development, Municipal Environmental Research Laboratory. Under the same contract a similar study was conducted on vermicomposting of municipal wastewater sludge (1).

The investigation combined review of pertinent technical and nontechnical literature, extensive written and telephone contact with numerous representatives of the vermiculture industry and researchers in the field, and a visit to a site where vermicomposting research is being conducted. Literature references were obtained through contacts with individuals working in the field, as well as through a computer-based literature search of related entries in the following data bases: AGRICOLA, BIOSIS PREVIEWS, COMPENDEX, EPB, NTIS, POLLUTION ABSTRACTS, and SSIE CURRENT RESEARCH.

BACKGROUND

Definition of Vermicomposting

Vermicomposting is the degradation of organic wastes by earthworm consumption. Some species of earthworm (*Eisenia foetida* and *Lumbricus rebellus*) thrive in managed conditions on a diet and substrate composed almost entirely of organic matter. They feed on the wastes, consume a portion of the organic matter and expel the remains as feces, or castings. If conditions are suitable, they will multiply. There is insufficient information to warrant speculation on whether the worms will increase or decrease in number when degrading solid wastes, however.

A portion of the wastes is usually not biodegradable and simply remains after processing as residue for disposal. Municipal solid wastes contain a high percentage of wastes that cannot be consumed by earthworms. The ratio of wastes that cannot be converted to castings would decrease if municipal wastes were separated at the source.

This report focuses on wastes normally collected by a municipality without a source separation program.

After the worms have fed on the waste and converted it into castings, they are usually separated from the castings. Worms can be recycled into new vermicomposting beds or, possibly, marketed in some form. Castings, once dried, have properties which might make them a desirable soils amendment. The end products of vermicomposting, therefore, are worms, castings, and solid-waste residue.

History of Vermicomposting

The role of earthworms in nature has been recognized since ancient times and was studied extensively by the biologist Charles Darwin in the late 19th century. Despite this awareness, and despite the fact that successful culture of earthworms need involve no new technology, the practices of raising worms (vermiculture) and using them for waste management (vermicomposting) have not been advanced until recently.

There are now numerous individuals, gardeners and entrepreneurs raising worms in a soil/peat/manure bedding in indoor bins or outdoor plots; most of those practicing vermiculture depend heavily on the baitworm market to realize some income from the business.

Only since 1970 has the vermicomposting of wastes (including municipal solid waste) been attempted at any more than barnyard scale. Pioneering efforts commonly mentioned in the literature (2, 3) include a demonstration project at Hollands Landing, Ontario (Canada), which was begun in 1970 and has since been operated under private ownership. A pilot-scale, one-time demonstration of vermicomposting municipal solid waste (MSW), was conducted in 1975 at Ontario, California. Neither operation was conducted under the controlled conditions that would yield reliable engineering design parameters. The Hollands Landing facility has vermicomposted small amounts of manure, food-processing wastes, and sludge (Klauck, personal communication); the Ontario, California, project involved the vermicomposting of municipal refuse in a program jointly conducted by the City and North American Bait Farms Inc. The short duration project involved a total of 10 tons of mixed municipal refuse, which was hand-picked to remove glass, metal, plastics, and rubber. The remaining 9 tons were windrowed adjacent to established earthworm beds at a wormbreeding farm. Reportedly, consumption of organics was 90-percent complete in 68 days. Only castings, bulky materials such as tree limbs, and inorganic residues remained.

In a later experiment at the same facility, a shredded and air-classified organic fraction of municipal solid waste was transported from a local resource-recovery facility. Reportedly, consumption of the wastes was faster and more complete than in the earlier experiments, even though the process was hampered by large quantities of plastic present in the waste and by very dry conditions resulting from the windrow's direct exposure to sunlight. No documentation is available on the amount of castings produced during the Ontario tests or their ultimate use.

Another demonstration of solid-waste vermicomposting was carried out in 1978-79 by the American Earthworm Company (AEC) in Florida (Wesley Logue, personal communication). This project involved vermicomposting, over a 12- to 18-month period, about 500 tons of municipal solid waste. Wastes were trucked to a 1-acre vermicomposting facility in Sanford, Florida, where cans, large objects, and newsprint were removed by hand. The remainder was fed to a hammermill shredder, which reduced the wastes to a 3-in particle size. The shredded waste was placed in windrows about 6 in deep, which were irrigated to increase moisture. Moisture levels achieved and other pertinent data are not known. AEC used approximately one tone of earthworms in the vermicomposting operation. Reportedly, some of the finished castings, which contained glass, were utilized by a local nursery. The facility is no longer in operation.

Other work has been carried out in Japan, where some pulp and food processing industrialists have turned to vermicomposting techniques for management of sludges and waste byproducts (4). Information was obtained through two sources in the vermiculture industry: AOKA SANGYO CO, LTD and TOYOHIRA SEIDEN KOGYO CO. The AOKA SANGYO CO. reports they have three 1,000-ton-per-month plants processing wastes from pulp and food processing companies (Shizuro Aobuchi, personal communication). The operation appears to be labor-intensive, and the economics appear to depend heavily on disposal fees paid by the industry. Reportedly about 400 tons of casting and 10 tons of earthworms are produced per month. The earthworms are freeze-dried and sold as fish feed. Worm castings are also sold.

The TOYOHIRA SEIDEN KOGYO CO. reports that rice plant straw, municipal sludge, sawdust, paper-making wastes, food-processing wastes and manure are vermicomposted (Katsumi Yamaguchi, personal communication). They estimate that about 20 private companies with monthly capacities of 2,000 to 3,000 tons are in operation. An additional 3,000 individuals may be vermicomposting 5 to 50 tons of wastes per month. However, these estimates are only approximate as the enterprises are not well-organized.

In Europe, no commercial-scale vermicomposting operations have been reported in the literature. A demonstration facility was recently established in Modena, Italy, however (Carla Chiesi, personal communication). Reportedly, a screened and composted municipal refuse is fed to Eisena foetida. In several other European countries, university laboratory research in waste vermicomposting is underway (5) (6).

Current Status

There is currently only one facility vermicomposting municipal solid wastes alone. That facility, in Ogden, Utah, at the Weber County Refuse Disposal Facility, is operated by Teledyne National, with Roger E. Gaddie of Annelidic Consumption Systems, Inc. (ASC) acting as a consultant on vermicomposting.

In August 1979, the vermicomposting of a small portion of the County's shredded wastes was begun. Some 23 tons of wastes were processed during the next several months. A description of the operation, including an estimate of waste-conversion rates and feasibility is presented in Section 3.

A vermicomposting operation in Ridgefield, Washington has used dairy manure, cannery wastes, paper mill sludge, municipal wastewater sludge and municipal refuse (1). The facility, operated by American Organic Farms, Inc., has recently received an experimental permit from the local Health Department to vermicompost the light fraction of source-separated garbage from a voluntary residential cross-section of Clark County, Washington. The material is ground when received on site and distributed on windrows which are also receiving liquid sewage sludge.

BIOLOGICAL INFORMATION

Earthworm Species Used in Vermicomposting

Only two species of earthworms -- *Eisenia foetida* and *Lumbricus rubellus* -- are commonly mentioned in the literature as suitable for use in waste-vermicomposting operations. Researchers have focused almost exclusively on the vermicomposting performance of these two species, which often share the common name of red worm. Other species have reportedly been utilized in pilot-scale studies, including *Lumbricus terrestris* (7) -- the nightcrawler -- and *Allolobophora calignosa* (2) -- the field worm, and these same species often will invade the lower reaches of composting windrows (8), but comparative discussions of their survival and performance in vermicomposting are not available. Recently, some interest has been shown in the so-called "African nightcrawler," *Eudrilus eugeniae*, but this worm requires near-tropical conditions of culture, and its performance in vermicomposting has been explored only in laboratory-scale studies (9, 10).

Not surprisingly, the two worms which appear best suited to the conditions of culture in vermicomposting occur in nature in enriched organic substrates. Both are small- to mid-sized earthworms classified by biologists among the lumbricids (Family Lumbricidae). They are pigmented surface-dwellers, found in nature in the upper 8 cm of the soil surface. Their surface-dwelling habit is not a coincidence: in nature, fresh organic matter is concentrated in the upper soil layers.

The distribution of E. foetida and L. rubellus in nature tends to be highly localized, as opposed to the widespread distribution of larger earthworm species that inhabit stable agricultural lands, fields, and woods. The "vermicomposting species" cannot thrive in unenriched environments; they require concentrations of organic matter. Conversely, the larger "agricultural species" -- such as the nightcrawler and field worm -- breed more slowly, adjust poorly to the managed conditions of vermicomposting, and cannot tolerate the temperature increases which can accompany bacterial decomposition of organic matter (8).

E. foetida is commonly known as the brandling worm (also red worm, red wiggler, manure worm, red-gold hybrid (8)). A relatively small worm of 4 to 8 mm diameter and 100 mm in length (8, 11), it is found in nature only in areas of high organic concentration -- in decaying logs, compost heaps, dung heaps. The brandling worm cannot, in fact, survive for long in average soils containing a greater proportion of mineral matter.

Two other characteristics distinguish E. foetida from most other earthworm species. E. foetida can tolerate somewhat higher temperatures than can most of the subsurface, burrowing species (12). This enables E. foetida to survive and feed in a compost heap sooner after the completion of its active, heating phase than can the other species (except L. rubellus). E. foetida is also more prolific than most other worms; it is the only cultivated species known to produce, on the average, more than one viable offspring per egg capsule (or cocoon).

L. rubellus (red worm, red wiggler, hybrid red worm, English red, Georgia red, California red) is similar in habit to E. foetida; it is found naturally in stream banks, organic leaf litter, and under dung pats in agricultural fields. Like E. foetida, this red worm breeds rapidly and has a relatively short development time to sexual maturity. Both L. rubellus and E. foetida can be found through all levels of a stabilized compost heap, whereas larger agricultural species are generally found only in the lower parts of the heap.

Table 1 presents vital biological data on E. foetida and L. rubellus, along with data on two non-vermicomposting species, L. terrestris and A. caliginosa, for comparative purposes. (From this point on in the report, references to "earthworms" should be taken to mean E. foetida and L. rubellus, unless otherwise specified.)

It is evident, from the table, that data gaps exist in some areas and that conflicts in data obscure true values in others. Some of the data conflicts can undoubtedly be attributed to differences in experimental techniques and to the fact that some observations were obtained in the field and others in controlled conditions favorable to growth. In the field, the period of growth is markedly affected by conditions existing when growth began. Sound experimental techniques will one day resolve these discrepancies and fill in other gaps in the knowledge of earthworm biology as it applies to vermicomposting.

Like all other earthworms, E. foetida and L. rubellus are hermaphroditic, each individual worm possessing both male and female sex organs. Reproduction normally occurs through copulation and cross-fertilization, following which each of the mated pair can produce cocoons (oothecae) containing one to 20 fertilized ova. Production of cocoons and emergence of offspring in these species are summarized in Table 1.

The resistant cocoons, tiny and roughly lemon-shaped, are usually deposited near the surface of the ground, except in dry weather when they are left at deeper levels. After an incubation period that varies with climatic conditions, the cocoons hatch. Young earthworms, white and only a few millimeters in length on emerging from a cocoon, gain their adult pigmentation within a day. Assuming favorable conditions, they will grow to sexual maturity within several weeks of emergence, although much depends on temperature, season, and conditions of culture.

Mature individuals are easily distinguished by the presence of a clitellum, the pale- or dark-colored swollen band, somewhat behind the genital pores. (The clitellum secretes the fibrous cocoon, and clitellar gland cells produce a nutritive albuminous fluid contained in the cocoon.) The worms usually continue to grow in size for several months after completing their sexual development.

Cocoon production, development and growth are much affected by seasonal climatic conditions. Cocoon production for L. rubellus, for example, is greatest in the months from June through September (8), and falls off directly with decreasing soil temperatures (we have not seen any discussion on whether it may also reflect an endogenous rhythm).

Although, theoretically, earthworms living in controlled conditions might be capable of extremely high rates of population growth -- with population doubling times of only a few days (13) -- most vermiculturists assume population doubling times of 60 to 90 days (8, 14). It is not known what generation times can be expected under the controlled, but periodically disturbed, conditions of vermicomposting.

In temperate zones, the seasons of greatest developmental activity are the spring and fall. Earthworms will enter a quiescent state (or diapause) when conditions are hot and dry, or very cold. Under such conditions, production of cocoons is ceased, and worm growth and development are slowed. Cold weather also lengthens the incubation period for cocoons. Cocoons produced during cold-weather months generally will not hatch until spring. Relatively little earthworm growth occurs in summer and winter, and individuals that emerge from cocoons in the height of summer can take up to twice as long to reach full development as those that emerge in autumn or spring.

Table 1

BIOLOGICAL DATA ON FOUR SPECIES OF LUMBRICID WORMS

	Vermicomposting Species		Non-Vermicomposting Species	
Characteristic	*Eisenia foetida*	*Lumbricus rubellus*	*Lumbricus terrestris*	*Allolobophora caliginosa*
Common name	. Brandling worm (red worm, manure worm)	. Red worm	. Night crawler	. Field worm
Color	. Brown and buff bands	. Reddish brown	. Brown violet	. Rose or brown red
Size of adult worms	. 4-8 mm diameter, 50-100 mm length	. 4 mm diameter, 70-150 mm length	. 8 mm diameter, 80-300 mm length	. 4 mm diameter, 40-200 mm length
Weight	. 2-3 mg at hatching . 0.4 g average adult . Up to 2.4 g in controlled conditions	*	. Average 5.0 g	*
No. of cocoons/year	. 11 (field conditions) . Up to 100 in controlled conditions	. 79-106	. Low	. 27
Size of cocoons	. 3.87 mm x 3.17 mm	. 3.18 mm x 2.76 mm	. 5.97 mm x 4.69 mm	*
Incubation period	. 3 weeks (25°C) . 11 weeks (field)	. 16 weeks (field)	*	. 19 weeks
No. of worms hatched/ cocoon	. 1.6 - 3.6 mean, varied seasonally . Average of 2.6 (and up to 6) among those that hatched--21.5% did not hatch	. Usually 1-2	. Usually 1-2	. Usually 1-2
Development to maturity	. 5-9 weeks (under controlled conditions, 18-28°C) . 47-74 weeks (field)	. 37 weeks (field)	. 52 weeks (field)	. 55 weeks (field)
Lifespan	. 4-1/2 years (protected)	*	. 6 years (protected)	. Long

*Information not found

In general, conditions of heat and drought are more dangerous to earthworms than those of wet and cold. For example, some worms have been shown to survive weeks of immersion in water, provided the water is kept aerated. Cocoons, however, can survive extremes of hot and cold within the range of normal climatic conditions.

In the field, average lifespans of *E. foetida* range from one to three years (11). *E. foetida* reportedly have lived for more than four years in controlled laboratory conditions. Among possible natural hazards, in addition to temperature and moisture extremes, are internal parasites (some microorganisms, platyhelminth worms, rotifers, nematodes and fly larvae) and predators (many birds, badgers, hedgehogs, moles, some snakes, certain beetles and their larvae, centipedes, and a few species each of carnivorous slugs, leeches and flatworms). In a municipal solid waste vermicomposting facility in Sanford, Florida, birds were found to be a problem (Wesley Logue, personal communication). But at the facility visited during this study (Ogden, Utah), there was not a predator problem.

Conditions of Culture

While details on the biology of earthworms seem scant or somewhat contradictory, the practical experience of worm breeders, worm farmers, and researchers has built a relatively consistent body of information on optimum conditions for supporting a worm population.

Temperatures --

Worms exhibit a fairly complex response to changes in temperature. In general, conditions that promote the most rapid feeding and conversion of waste to castings are found in the temperature range of 13°C to 22°C, averaged from results obtained by most workers. Both *E. foetida* and *L. rubellus* will prefer substrate temperatures within this moderate range, but the upper limit of temperature preference is somewhat lower for *L. rubellus* at 18°C. These moderate temperatures represent practical criteria for design and operation of vermicomposting systems.

At soil temperatures below 10°C, worms' feeding activity is described as greatly-reduced to nonexistent (7); below 4°C, production of cocoons and development of young earthworms cease (11). Worms will tend to hibernate and migrate to deeper layers of the windrow or into the soil for protection. Worms can become acclimated during the fall months to the temperatures they will encounter at deeper substrate levels in the winter, but they cannot survive in freezing temperatures.

At temperatures above the optimum range, up to 25°C to 27°C, the worms' performance depends in part on their acclimation to the higher temperatures. Worms raised from hatching to adulthood under controlled conditions at 25°C have been shown to feed and grow well, and to develop and reproduce at rates faster than worms raised at lower temperatures or in the field (8, 15). For worms not acclimated to higher temperatures, activity is significantly reduced at 25°C, and there may be loss-of-weight and mortality (7, 16).

The unfavorable effect on worms of high (25°C and above) temperatures is not entirely a direct effect. Warm temperatures also support accelerated chemical and microbial activities in the substrate; the increased microbial activity tends to use up available oxygen, to the worm's detriment (7). These temperature studies were conducted mostly with sludge as feed; none were conducted with municipal solid waste.

pH --

Earthworms generally prefer neutral soils (2), and both _E. foetida_ and _L. rubellus_ find their optimum environment at pH 7.0 to 8.0, neutral to mildly alkaline (8). Worms will avoid acid soils of pH less than 4.5, and prolonged exposure to such soils acts as a violent contact poison with lethal effects (11).

Minor increases in acidity caused by addition of fresh wastes to the vermicomposting bed will be neutralized by the worms' intestinal secretions and excreted ammonia (11). Operators can also control acidity by adding lime (17) or limestone flour (13), as necessary.

Moisture Content --

In nature, the greatest number of worms will be found in the soils of 12 to 30 percent moisture (8). In vermicomposting, the optimum range of moisture content has been reported at 50 to 90 percent. Above 80 percent moisture, conditions of poor oxygen transfer might interfere with the worms' feeding. Municipal solid waste has a moisture content ranging from 20 to 40 percent. Periodic irrigation is required to increase the moisture content. The worms' feeding rate apparently is independent of moisture content, as long as a threshold value of moisture (50 percent) is present (18).

Aeration --

Earthworms have no specialized respiratory organs; oxygen diffuses in through skin layers of the body wall, and carbon dioxide diffuses out. Earthworms are sensitive to anaerobic conditions. Their respiration rates are depressed in the presence of low oxygen concentrations -- by 55 to 65 percent, for example, in the presence of oxygen at one-fourth its normal partial pressure (11). Feeding activity might be reduced under these suboptimal conditions (15). _E. foetida_ have been reported to migrate _en masse_ from a water-saturated substrate in which oxygen is being depleted, or in which carbon dioxide or hydrogen sulfide is accumulating. The situation is made more critical by oxygen requirements that may increase by a factor of 10 as temperatures increase from 9°C to 27°C (11).

In the vermicomposting operation, aeration requirements can be met by (1) mechanically turning or tilling the beds at regular intervals, (2) maximizing surface area in the piles by keeping the windrows shallow, (3) protecting against bed saturation by enclosing the vermicomposting facility, and (4) maintaining temperatures within the optimum range for feeding by heating or cooling enclosed facilities. Some researchers argue against mechanical turning, both because it can cause trauma to the worms and because it can redisperse castings into the substrate, which may produce toxic effects in the worms (15).

Nitrogen and Other Substrate Minerals --

Earthworms reportedly thrive in a medium of 9 to 15 percent protein (17). Fresh bovine feces contain about 14 to 15 percent protein (17), sludge can vary from 12 to 38 percent protein, and unsorted mixed municipal refuse might contain only about 4 percent protein, depending on sources (19). A low to moderate carbon-to-nitrogen (C:N) ratio is considered desirable, with worms showing maximal weight gain in the C:N range of 15:1 to 35:1 (20). Only the most biodegradable fractions of municipal solid waste -- such as yard wastes and food wastes -- fall into this optimum range; unsorted mixed municipal refuse will have a C:N ratio on the order of 50:1 (19).

At Johnson City, Tennessee, refuse with an initial C:N ratio of between 40 and 50 was reduced to between 28 and 35 during six weeks of composting (21). The vermicomposting operation envisioned in this report allows for composting of several weeks' duration prior to the addition of earthworms. Therefore, the vermicomposting operator should be testing for the C:N ratio of the wastes and make an attempt to keep the ratio low. One possible method is the addition of a nitrogen source such as sludge or manure to the solid waste.

PHYSICAL AND CHEMICAL CHANGES DURING VERMICOMPOSTING

As the worms eat and digest waste, they expel the digested material as castings. The large particles and irregular shapes of wastes are reduced by the worms to much smaller particles of relatively uniform shape and size.

In fact, when dry, castings have the appearance of sand pebbles of roughly oblong shape, with approximate dimensions of 0.55 mm in diameter and 1.00 mm in length (22). Their odor is that of fresh earth or compost and is not noticeable unless an effort is made to smell the castings close up.

Worms secrete a mucus membrane around the castings (15). It is theorized that the membrane might serve to protect the worms from their own feces; castings are generally toxic to the species of worm which produces them. An additional benefit of the membrane formation process might be that castings are kept separate from each other, thereby increasing the exposure of the castings; surfaces to air.

SECTION 3

FACILITIES REQUIRED FOR VERMICOMPOSTING

RESULTS OF OGDEN, UTAH, VERMICOMPOSTING PILOT PROGRAM

As noted in Section 2, the vermicomposting pilot facility being operated at the Weber County Refuse Disposal Facility in Ogden, Utah, by Annelidic Consumption Systems, Inc., is the only currently operating vermicomposting facility in the United States exclusively utilizing municipal solid waste.

At the Weber County Refuse Disposal Facility, which is operated by Teledyne National, about 350 tpd of mixed, residential and commercial wastes are burned. Before combustion, the wastes are shredded to a nominal size of 6 to 8 in., and ferrous metals are removed by a magnetic pulley.

In early August 1979, operators at the Weber County Facility used front-end loaders to transfer approximately 47 cubic yards of shredded waste to three windrows in an area prepared for a sanitary landfill operation (Figure 1). Based on a field measured density of approximately 240 lb/cu yd, about 5.6 tons of wastes were windrowed. The windrows, each measuring 20 to 35 ft long and about 9 ft wide, were spaced 10 ft apart. The maximum depth of each windrow was approximately 3 ft. The windrows were watered to increase the moisture content.

After several days, temperatures began to increase in the windrows due to bacterial breakdown of organic matter (composting). If composting had been carried out properly, temperatures of 50° to 60°C should have been attained. The elevated temperatures continued through 27 August; windrow temperatures on that day were measured at about 32°C. During this period it is unlikely that aerobic thermophilic composting was achieved.

Apparently, temperatures in the windrows would have dropped more rapidly had the wastes been kept sufficiently moist by facility operators. Once windrows were wet down on 27 August, temperatures dropped to 24°C -- within the range at which vermicomposting can begin. At this point, some 1,450 lb of earthworms were applied to the windrows. The worms reportedly infiltrated the windrows within a day.

On three occasions during the next 35-day period, 1-ft increments of shredded and unshredded wastes were added to the top of each windrow. About 36 cu yd (4.4 tons) were added during this period; in all, a total of 83 cu yd (and 10 tons) of solid wastes were vermicomposted. For the next 2 1/2 months, the earthworms converted the wastes to castings.

Figure 1. (left) Ogden, Utah, vermicomposting pilot facility

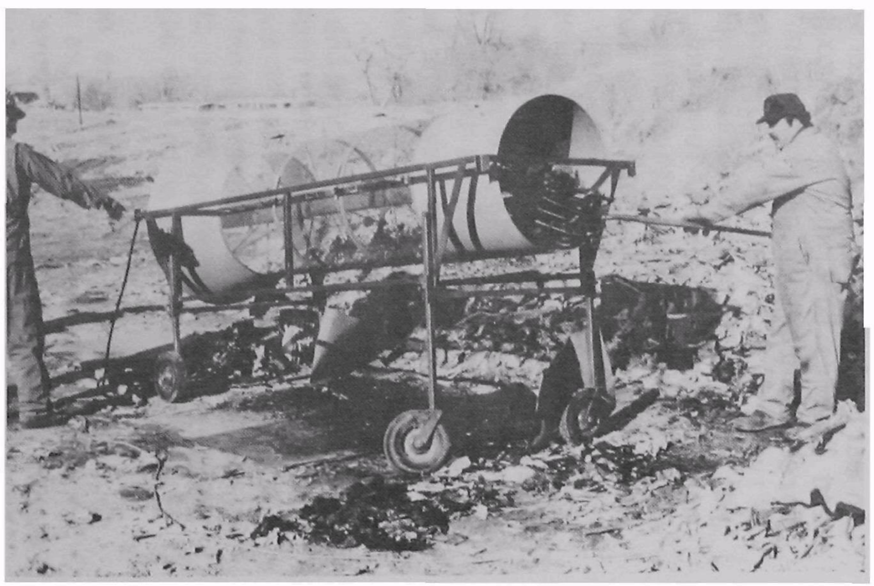

Figure 2. (left) Rotary screening device

Figure 3. (above) Solid waste residue

On 31 October 1979, four additional windrows were constructed between existing windrows. The new windrows contained about 13 tons of solid wastes and occupied about 1,050 sq ft. No new earthworms were added to these windrows. Some of the earthworms migrated from the first three windrows to the second set of windrows in search of more attractive food sources.

CDM engineers were on-site when facility workers began harvesting portions of the first three windrows on 14 December 1979, 100 days after earthworms were first added and about 130 days after wastes were first windrowed. In the judgment of Ronald E. Gaddie of Annelidic Consumption Systems, Inc., 90 percent of the wastes had been converted at this point. Based on the screening results obtained later, however, a much lower percentage had been converted.

Harvesting was accomplished using an inclined cylindrical, rotating screen driven by a small motor, a type of device commonly used in vermiculture (Figure 2). In normal operation, this type of screen separates castings (which fall through the screen) from earthworms and residual solid waste (which travel the length of the screen and are discharged). Because of the large amount of plastic in the waste stream, however, and perhaps because not all wastes had been shredded properly prior to windrowing, the harvesting screen did not work very well. It was apparent that less than 50 percent of the material fed to the device was screened out as castings. Most of the material either had to be removed by hand from the front of the machine, which clogged repeatedly, or was discharged through the length of the harvester as residue. Very few earthworms were separated. Figures 2 also shows the castings recovered and the residue discharged. Figure 3 is a closeup of the discharge end of the screen.

To determine the physical facilities required for composting, CDM estimated the rate of waste conversion at the Ogden pilot facility. In the literature, estimates of worms' performance in vermicomposting vary widely. Entrepreneurs working in the vermiculture industry routinely report that worms will consume one-half to twice their weight in waste each day. To provide a rational basis for the design of facilities, we calculated a consumption rate based on the experience at Ogden.

At Ogden, 10 tons of wastes were processed during a 110-day period using 1,450 lb of earthworms. This time does not include 3 weeks of thermophilic composting prior to the introduction of earthworms, even though this preliminary composting is essential in order to maintain optimum temperatures during vermicomposting. The calculated conversion rate of vermicomposting at Ogden is, therefore, about 0.13 lb waste processed/lb of earthworms per day.

Area requirements for vermicomposting are determined from the ratio of the weight of earthworms utilized per unit of area. At Ogden, 1,450 lb of earthworms were applied to about 800 ft of windrows. The resulting ratio of 1.8 lb/sq ft compares with ratios used in vermicomposting of wastewater sludge (0.4 to 2.3 lb/sq ft).

Based on the conversion rate (0.13 lb wastes/lb earthworms per day) and area requirements (1.8 lb earthworms/sq ft of wastes) observed at Ogden, a loading rate of 0.23 lb/sq ft per day is calculated. Stated another way, each ton/day of waste requires about 0.2 acre, plus about 20 percent to allow for composting before worm addition. In practice, earthworms would be added to an initial set of windrows. After 130 days, new windrows would be constructed between the existing windrows. This allows the earthworms originally added to the first set to migrate to the second set of windrows. Then the initial set of windrows are removed and screened. In this way, the land is used in 130-day cycles and earthworms are reused.

ACS speculates that under more favorable climatic conditions, and/or with an earthworm that is acclimated to solid wastes, only 70 days would be required for conversion (Gaddie, personal communication). If this were so, only 0.13 acre would be required for each ton/day of municipal wastes. Additional research could establish the time required for conversion under various loading and climatic conditions.

SELECTED FACILITY CAPACITY

For this report, CDM examined a hypothetical small facility and large facility. The small facility was defined as one receiving 100 tons per day of wastes, 6 days per week, representing the total mixed residential and commercial wastes of a municipality of about 50,000 persons. Bulky items such as "white goods" (large household appliances) and demolition wastes would be managed by separate collection. For a facility of this size, three other candidate waste processing techniques would be (1) sanitary landfill, (2) incineration of wastes in a modular combustion unit (MCU), a technique becoming economically attractive for small- and medium-sized communities with a large and stable market for the recovered energy and (3) windrow composting.

The large facility would receive 1,200 tpd of wastes, 6 days per week, representing residential and commercial wastes generated in a city or metropolitan area of about one-half million persons.

Area requirements for windrows alone, in the 1,200-tpd facility, would total 250 acres. Dedication of this much land to the vermicomposting process is inconceivable and mechanization (for example in silos) has not been demonstrated. In this report, therefore, it is assumed that the municipality would already have in operation a 1,200-tpd facility converting solid waste to refuse-derived fuel (RDF) and recovering steam energy from incineration of the RDF. Only a small portion (92 tpd) of the shredded wastes would be diverted to the vermicomposting facility. This diversion would allow for production of humus material for local use. The fact that the necessary preprocessing would have been completed as part of an existing processing train would be expected to make the economics of vermicomposting as attractive as possible for a facility of this size.

Technical criteria and costs for vermicomposting facilities serving communities of population 50,000 and 500,000, respectively, are developed as follows.

DESIGN CRITERIA AND MATERIALS BALANCE

Figure 4 presents a materials balance adapted from Gaddie for a waste stream from which a large portion (36 percent) would have been removed before vermicomposting. Substances removed would include paper, glass, aluminum, ferrous metals, and other items (23). Of the 64 tpd of solid waste to be vermicomposted, about 18 tpd would be ultimately landfilled. Of the remaining 46 tpd, about 70 percent (33 tpd) would be converted to castings, and 30 percent (13 tpd) would be volatilized or account for reduction in moisture.

Figure 5 shows a materials balance for a waste stream exposed only to processes of shredding and ferrous removal prior to vermicomposting. In this case, approximately 92 tpd of the total received would go to vermicomposting. The remaining 8 tpd would consist of ferrous material recovered for sale. Actual percent ferrous recoverable may range between 6 and 10 percent, depending on local waste composition and facility design and operation. The vermicomposting facility would also receive the 92 tpd of shredded and ferrous wastes removed from the 1,200 tpd facility.

Of the 92 tpd diverted to vermicomposting, about 31 tpd -- including glass, rubber and wood wastes -- would be landfilled. The amount of castings produced would be 70 percent of the remaining portion, or 43 tpd. The other 30 percent (18 tpd) would be volatilized or account for reduction in moisture.

It is important to note that none of the above estimates has been verified at actual demonstration facilities. The rotary screening operation at Ogden has not yielded the quantities of castings used for this report. As noted above, however, much of the work at Ogden has been carried out at less than optimum conditions and with some unshredded wastes present. The materials balance is optimistic in order to provide the most favorable economic analysis.

To determine the area required for vermicomposting, the assumptions presented in Section 2 are followed. Total residence time would be 110 days, resulting in a loading rate of 0.23 lb waste/sq ft per day. An additional 20 percent is added to the area to provide space for preliminary composting. For a daily average loading of 92 tpd, the windrow area requirement would be 22 acres; a total of 23 acres of land has been allocated for windrowing to account for an access road.

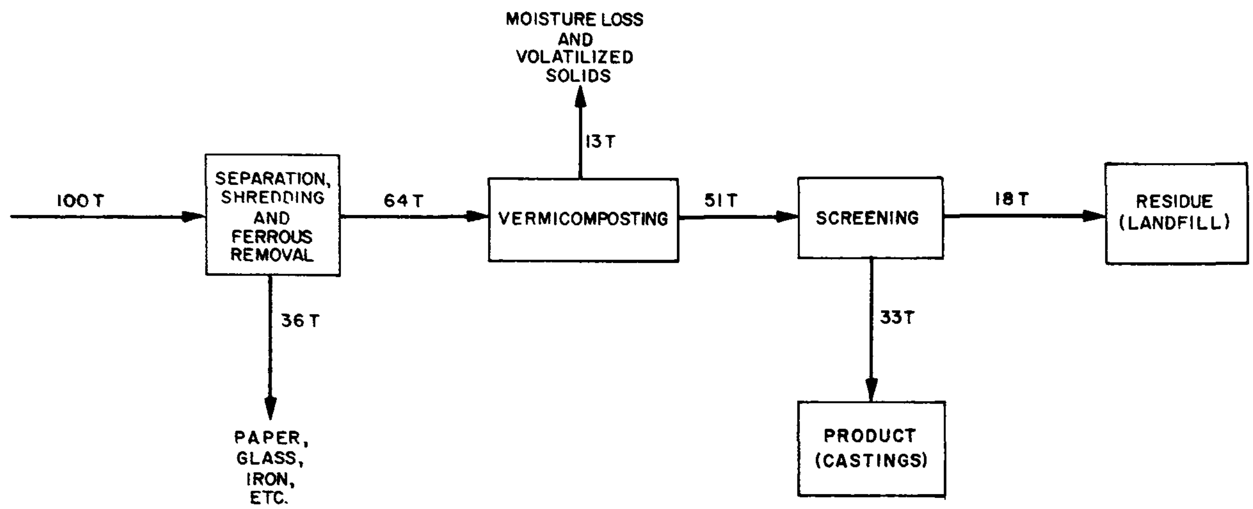

FIGURE 4. VERMICOMPOSTING MATERIALS BALANCE

(BASED ON ESTIMATES DEVELOPED BY ANNELIDIC CONSUMPTION SYSTEMS, INC.)

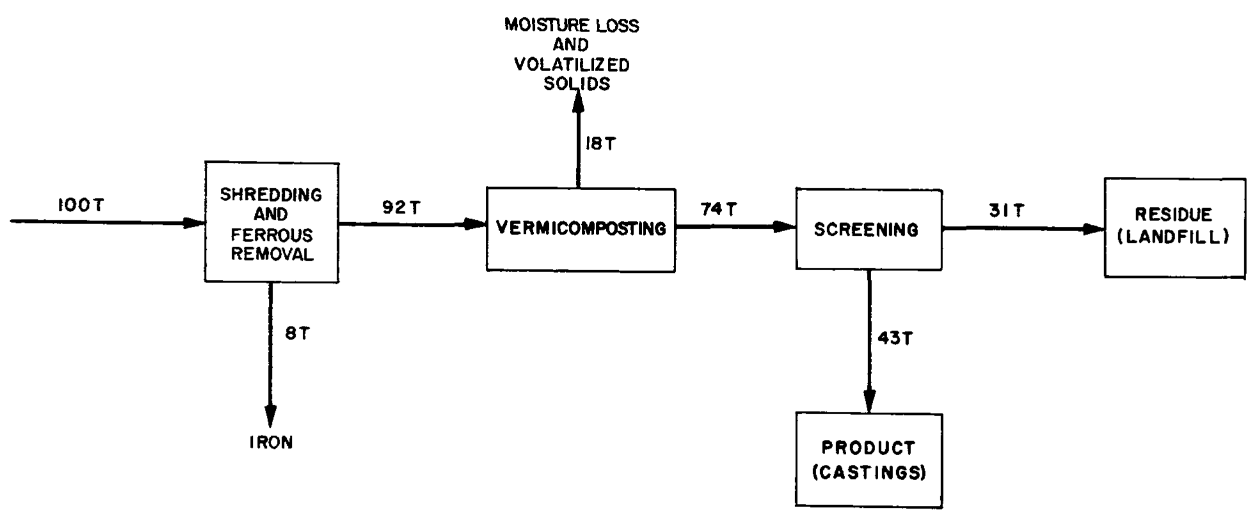

FIGURE 5. VERMICOMPOSTING MATERIALS BALANCE

DESCRIPTION OF PREPROCESSING FACILITIES

Preprocessing facilities can be subdivided into units for receiving, shredding, magnetic separation, and storage of solid wastes. Figure 6 shows preprocessing, vermicomposting and residue disposal facilities for the 100-tpd facility. For the 1,200-tpd facility, separate preprocessing would not be required and shredded wastes would be introduced directly to the windrows.

For a 100-tpd facility, only ferrous removal and shredding could be economically justified. Aluminum recovery may or may not be justified, but its exclusion from this analysis will not affect the cost of vermicomposting relative to other methods. Further preprocessing, including (1) the mechanical removal of glass and paper and (2) fine or secondary shredding, is not economically feasible at a small facility. These assumptions are based on the findings of recent solid waste management studies (24, 25, 26). The steps of preprocessing described below apply only to the 100-tpd facility serving a community of 50,000, because preprocessing for the 1,200-tpd RDF facility with a 100-tpd vermicomposting side operation is completed in conversion of the total waste stream to RDF.

Receiving --

Collection and transfer of municipal solid waste would terminate at a receiving building, where refuse would enter the preprocessing system. There, the transfer-haul trucks would tip their solid waste onto the floor, where a front-end loader would stockpile it into the center of the building. Large bulky items, such as tree stumps and white goods, would be sorted out of the process stream by front-end loader, prior to dumping onto conveyors. Hand-sorting could be performed during the conveyor stage to eliminate a large portion of other unprocessable items. Refuse then would pass into the shredder building.

Shredding --

A shredder reduces volume by about 50 to 70 percent. Depending on initial moisture content, however, only about 7 percent of the initial weight may be lost (27). In reducing refuse to a relatively small and uniform size, the shredder tends to make refuse more homogeneous. This facilitates further handling, sorting and processing of the wastes and, in the case of incineration modes of disposal, produces a fuel product with more highly predictable combustion properties. Particle size of the product could be varied to meet the requirements of vermicomposting. A shredder would be expected to reduce refuse to a nominal 4- to 6-inch size.

Annual maintenance costs for the shredder and building would be high in comparison to other equipment, due in part to the relatively frequent occurrence of damaging explosions.

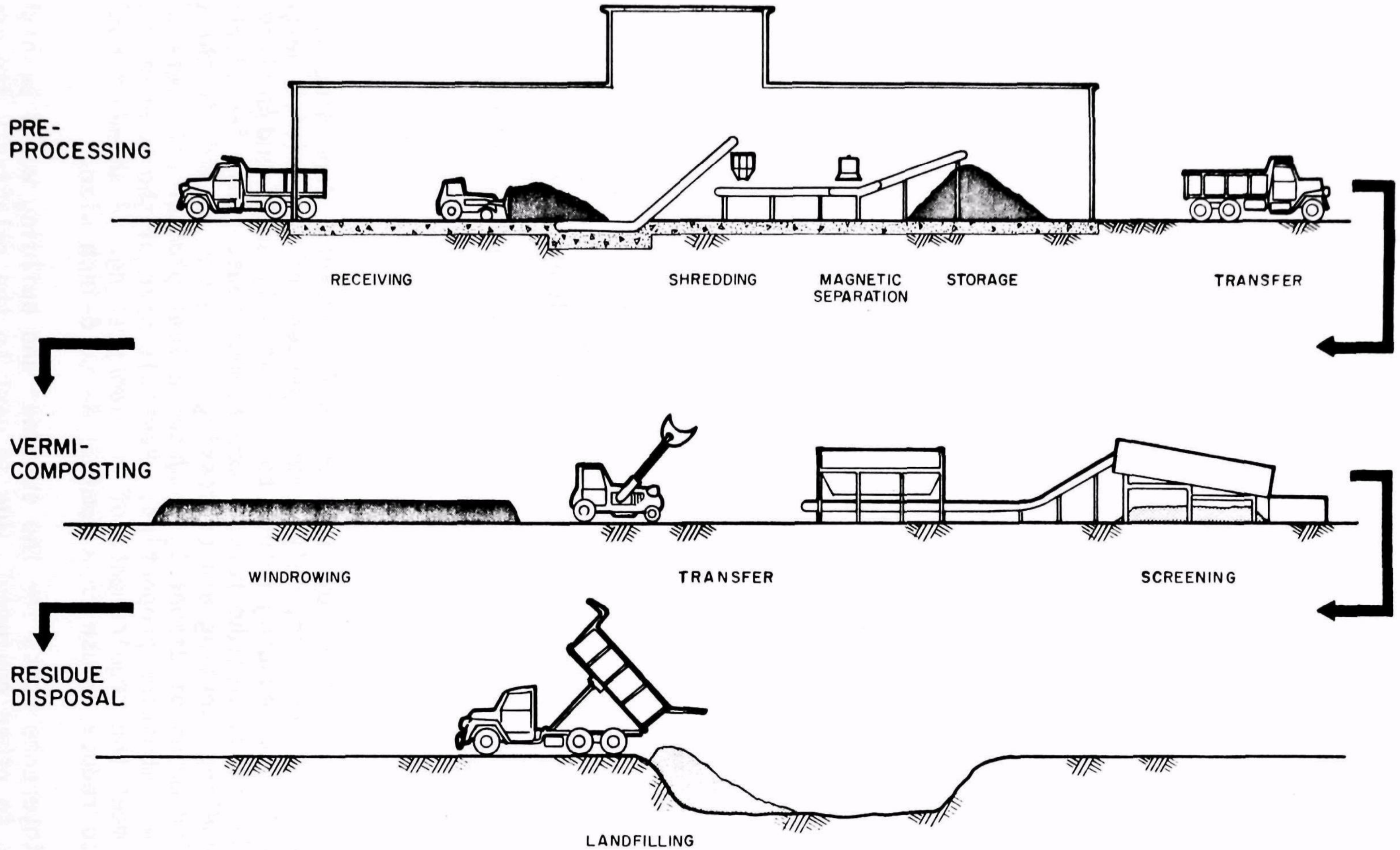

FIGURE 6. VERMICOMPOSTING FACILITIES

According to an industry report (28), significant explosions can be expected at a solid waste shredding facility on the average of four times per year. One of these explosions can statistically be expected to cause major damage to the facility.

Magnetic Separation --

The magnetic properties of iron and steel make ferrous recovery one of the easiest materials-separation processes to implement in solid-waste management. Three basic types of magnetic separators have been used successfully in recovering ferrous items from shredded refuse: drum magnets, single magnet-belt separators, and multiple magnet-belt separators. These magnets are usually suspended over the end of a conveyor which carries shredded solid wastes. As the wastes pass by or under the magnet, ferrous metals are picked up and thrown or diverted into a separate stream.

Magnetic separation may be accomplished at any of several different points in a resource-recovery facility: usually following shredding but before density/size classification. The technique can also be used to separate potentially marketable post-incineration scrap from incinerator residue. The specific point to perform magnetic separation and the type of magnet used depend upon the particular market specifications, the market location for the ferrous scrap, and requirements of other separation processes. The recovered ferrous metals may then be sold to secondary material markets to help offset the capital and operating costs for processing.

DESCRIPTION OF STORAGE FACILITIES

In the smaller facility (100 tpd), the shredded product would be bunkered in a passive, three-walled tipping floor arrangement. The waste would then be fed to trucks by front-end loader and transported to the vermicomposting facility.

For the larger, 1,200-tpd RDF facility, the processed waste (RDF) would pass from the shredder building via conveyor to a storage bin. This facility would incorporate live bottom hoppers to feed conveyors which, in turn, would feed semi-suspension boilers or transfer-haul vehicles. Prior to reaching the storage bin, approximately 92 tpd of processed waste would be redirected via a reversable conveyor that would feed into trucks dedicated to hauling the processed waste to the vermicomposting facility.

The storage bin would have a 2-day storage capacity to handle the incoming wastes during vermicomposting and/or incinerator down-time.

DESCRIPTION OF VERMICOMPOSTING AND RESIDUE DISPOSAL FACILITIES

Shredded wastes with ferrous material removed would be discharged to bunker storage or directly to trucks destined for the vermicomposting facility.

The 92-tpd remaining after removal of ferrous material would yield a volume of about 900 cu yd/day at a density of approximately 200 lb/cu yd. Wastes would be recovered from the bunker by a 3-cu yd capacity front-end loader and placed in a 16-cu yd capacity dump truck.

Figure 6 shows the major steps in vermicomposting: windrowing and screening. Shredded wastes would be trucked to nearby windrows and spread by a second smaller loader. This method would be less expensive than utilization of loaders alone because of the distance and time required to travel to the windrows in a typical operation.

One possible site arrangement would be a configuration approximately 1,000 ft square. About 95 500-ft-long windrows could be accommodated on each side of a central access aisle. Each windrow would be 10 ft wide and 3 ft deep. Initially, wastes would be windrowed in every other row. About three 500-ft windrows would be constructed daily, and, during the first month after earthworm addition, three additional top-dressings of wastes would be applied to each windrow, as at Ogden. After one-half of the total area for windrows was constructed, shredded wastes would be windrowed on the alternate rows. The site would be equipped with a sprinkler system for initial moistening of the windrows to achieve the proper moisture content.

Based on pilot-plant experience, earthworms would be added to one-half of the windrows (480,000 sq ft) at a rate of 1.8 lb/sq ft; a total of approximately 430 tons of earthworms would be required for this initial earthworm addition. Earthworms recovered during harvesting would be reused for new windrow construction. Several researchers ((23) and J. McClarran, personal communication) have suggested that excess earthworms could be produced during vermicomposting, but more research is needed to determine the rates at which earthworms will breed under conditions of vermicomposting. In order to reduce capital costs, several vermicomposting operators have suggested that only one-fourth to one-third of the total required stock might be purchased initially, with the process phased into full operation over a period of several months as excess earthworms are produced. For this report, we have assumed that one-half of the total area would be stocked with purchased earthworms because of the lack of data on earthworm production during vermicomposting. Even if minimal costs were included for earthworm purchase, the net costs of vermicomposting would be relatively unchanged with respect to other alternatives.

After a total residence time of 130 days, the wastes would be recovered from the windrows by a front-end loader. At this point, nearly all the biodegradable portion that can be converted by earthworms would have been consumed. Approximately 450 cu yd (74 tons) of material would be removed daily. The wastes would be transported by front-end loader to a movable surge hopper located above a central collecting conveyor, which would move material to the screening area.

Two rotary harvesting screens, each approximately 6 ft in diameter and 12 ft long, would be employed; one screen would serve as a standby. The screens would be fed directly by the variable-speed conveyor. Castings would fall through the screen to a product storage pile. The operation could be expected to produce approximately 300 cu yd (43 tons) of castings per day. Residual waste would be discharged at the low end of the inclined screen to a conveyor, which would remove the material to another storage pile. These wastes -- totalling about 150 cu yd, or 31 tons of residue per day -- could then be recovered by a front-end loader and trucked to the landfill.

The harvesting screen would also be able to collect earthworms for reuse. The compacted residue volume would be about 19 acre-ft per year. Based on a total lift of about 10 ft, about two acres of landfill would be required each year. For the 20-yr planning period considered in this report, a 38-acre landfill site would be required. The site might be developed in 5- to 10-acre modules.

SECTION 4

ECONOMICS OF VERMICOMPOSTING

BASIS OF COSTS

In this section, costs are estimated for a vermicomposting facility based on requirements developed in Section 3. All costs, which are based on Spring 1980 prices, include total capital costs, amortized capital costs and annual operating costs. The net cost for each alternative is expressed in total annual dollars, including credit for revenues, and in terms of cost per ton processed. Cost per ton is based on processing 31,200 tons of municipal solid waste per year (100 tpd, 6 day/wk operation).

Capital costs are amortized at a 7 percent interest rate over a 20-yr planning period, according to EPA cost-effectiveness analysis guidelines. Structures are assumed to have a service life of 20 yr, equipment a service life of 10 yr. Land was assumed to have a salvage value after 20 yr equal to the purchase price. Land costs were taken as $5,000/acre, but this will vary considerably from site-to-site with much higher costs in urban areas.

COSTS OF VERMICOMPOSTING

The costs of vermicomposting can be divided into three components: preprocessing, vermicomposting, and residue disposal. As was noted in Section 3, of the 100 tpd received at a facility, about 92 tpd would be vermicomposted, and, of this, about 31 tpd would remain as residue requiring landfill disposal. The same costs are used for the 92 tpd routed to vermicomposting for the 1,200-tpd facility.

Preprocessing Costs

Table 2 shows the costs of preprocessing. Site acquisition (two acres) and site development (including utilities) would total about $220,000. Three buildings (receiving, shredding and storage) would cost about $730,000. Equipment costs would be $845,000, with the shredder accounting for about one-half of the costs. Total costs are approximately $1,800,000, or about $206,000 on an equivalent-annual-cost basis.

Table 2

COSTS OF PREPROCESSING FOR A 100-TPD VERMICOMPOSTING FACILITY

Capital Costs		Cost	Service Life	Amortization Factor	Annual Cost
Site Acquisition & Development		$160,000	-	0.070	$ 11,000
Utilities		60,000	20	0.094	6,000
Structures:					
Receiving	270,000				
Shredding	260,000				
Storage	200,000				
		730,000	20	0.094	69,000
Equipment:					
Apron Feed Conveyor	280,000				
Shredder	430,000				
Ferrous Magnet	45,000				
Ferrous Conveyor	15,000				
Front End Loader	75,000				
		850,000	10	0.142	120,000
Total (Rounded)		1,800,000	-	-	$210,000
Operating Costs					
Labor					123,000
Maintenance					70,000
Power					33,000
Fuel					15,000
Subtotal (Rounded)					$240,000
Total (Rounded)		$1,800,000			$450,000

Operating costs include labor, maintenance, power, and fuel. Labor costs are based on six employees: a supervisor, a loader operator, a mechanic and three laborers. Maintenance costs include periodic major overhaul and repair of facilities to account for expected shredder explosions. Power costs include operation of conveyors, the shredder, lighting and HVAC and are based on $0.05/kWh. Fuel (diesel and oil) costs for the front-end loader are based on January 1980 prices. Total annual operating costs are $240,000.

Total annual costs, including amortized capital, are about $450,000.

Vermicomposting Costs

The costs of vermicomposting facilities are shown in Table 3. Total land area requirements for vermicomposting are 23 acres. Costs for land and site development total $20,000/acre, including grading and drainage facilities. Equipment costs for vermicomposting, at $545,000, include stationary and mobile materials-handling equipment, an irrigation system, and two rotary screens for product harvesting.

In order initially to stock 50 percent of all windrows at 1.8 lb/sq ft, 430 tons of earthworms would be required. Earthworm prices generally range between $2 and $3 per pound. At an average of $2.50/lb, a total capital investment of $2,150,000 is required.

Vermicomposting entrepreneurs have suggested that earthworms would have a resale value at the end of the 20-yr project life equal to or exceeding the initial purchase price. Therefore, capital cost estimates should be based on the differential between initial purchase price and final sale price, or about $0.50/lb. Because the market for worms bred in a municipal solid waste vermicomposting operation is unknown, however, we have used the $2.50/lb estimate.

Total capital costs for vermicomposting are $3,150,000, or an equivalent annual cost of about $310,000. Operating costs include labor, maintenance and utilities. Six persons would be required to operate a 100-tpd vermicomposting facility: a supervisor, screen operator, two loader operators and two truck drivers. Total labor costs are $129,000. Maintenance of equipment is about $16,000/yr. Utility costs ($67,000) include fuel for loaders and trucks, power for conveyors and pumps, and water for irrigation. Total operating costs are about $210,000.

Total annual costs for the vermicomposting facilities, including amortized capital, are about $520,000.

Residue Disposal Costs

Costs for residue disposal in a landfill are shown in Table 4. As was presented earlier, about 19 acre-ft per year of residue is generated at a 100-tpd vermicomposting facility. Based on a 20-year planning period, and

Table 3

COSTS OF VERMICOMPOSTING FOR A 100-TPD VERMICOMPOSTING FACILITY

Capital Costs	Cost	Service Life	Amortization Factor	Annual Cost
Site Acquisition & Development	$460,000	-	0.070	$ 32,000
Equipment:				
Conveyors $300,000				
Screens (2) 30,000				
Irrigation System 15,000				
Front End Loader 75,000				
Front End Loader 25,000				
Dump Trucks (2) 100,000				
	545,000	10	0.142	77,000
Earthworm Stock	2,150,000	20	0.094	202,000
Total (Rounded)	$3,150,000			$310,000
Operating Costs				
Labor				129,000
Maintenance				16,000
Utilities				67,000
Subtotal (Rounded)				$210,000
Total (Rounded)	$3,150,000			$520,000

Table 4

COSTS OF RESIDUE DISPOSAL FOR A 100-TPD VERMICOMPOSTING FACILITY

Capital Costs	Cost	Service Life	Amortization Factor	Annual Cost
Site Acquisition	$190,000	-	0.070	$13,000
Site Development	310,000	20	0.094	29,000
Equipment	75,000	10	0.142	11,000
Total (Rounded)	$575,000			$50,000
Operating Costs				
Labor				22,000
Fuel				15,000
Maintenance				5,000
Subtotal (Rounded)				$40,000
Total (Rounded)	$575,000			$90,000

10-ft lift available, a 38-acre site is, therefore, required. Initial site acquisition cost is $190,000. Although site development cost is based here on the total 38 acres, the site development would, in actual practice, occur in 5- to 10-acre increments throughout the life of the project.

A truck loader costing about $150,000 is required for the landfill operation. For this report, we have used one-half of the total estimated capital and operating costs, because the loader would only be utilized for disposal of vermicomposting residues about 50 percent of the time. We have assumed that the remainder of available loader time could be dedicated to another municipal function. Total capital costs for residue disposal are $575,000, or about $53,000/yr taking into account varying service lines.

Annual operating costs for the landfill operation include labor ($22,000), fuel for equipment ($15,000) and maintenance ($5,000). Total operating costs are $42,000.

Total annual costs for residue disposal, including amortized capital costs, are $95,000.

Table 5 presents a summary of the total costs of vermicomposting including preprocessing, vermicomposting and residue disposal. Total capital costs for a 100-tpd facility are $5,525,000, or an equivalent annual cost of $1,065,000. Based on processing 31,200 tons of municipal solid waste per year, the unit cost is $34/ton. This is a disposal cost. It does not include the collection costs that are normally incurred by a municipality.

Potential Product Revenues

Net costs include the credit for revenues generated by the sale of ferrous metals and earthworm castings. Based on spring 1980 secondary-materials market prices reported in Iron Age Magazine Journal, ferrous metals can be sold for $30 to $50/ton assuming minimal transportation costs. Assuming recovery of 2,500 tons/yr, the revenue is between $75,000 to $125,000.

There are no known markets for the sale of earthworm castings derived from municipal solid waste. There are some operations involving the sale of horticultural potting mixes that are composed, in part, of castings produced from the vermicomposting of manure and other nonmunicipal wastes. Earthworm castings might be compared with some validity to compost, which is usually given away or sold for less than $5/ton. Earthworm castings cannot be compared to dried sludge products such as Milorganite, which have much higher nitrogen and phosphorus contents.

Several vermicomposting operators and researchers have suggested potential market prices. Gaddie has suggested that earthworm castings produced from municipal solid waste would be sold for $28/ton. Ervin, in an economic evaluation of a vermicomposting operation in Florida, has suggested a sale price of $15/ton (29). For this report, we have used a range of $0 to $15/ton, reflecting the lack of marketing experience. Based on 13,400 tons of castings recovered per year, annual revenues are $0 to $200,000.

Table 5

TOTAL COSTS OF VERMICOMPOSTING MUNICIPAL SOLID WASTES FOR A 100-TPD FACILITY

	Capital	Annual
Preprocessing Facilities	$1,800,000	$450,000
Vermicomposting Facilities	3,150,000	520,000
Residue Disposal	575,000	90,000
Subtotal (Rounded)	$5,500,000	$1,060,000
Revenue:		
Ferrous Metals	-	75,000-125,000
Earthworm Castings	-	0-200,000
Net Cost (Rounded)	$5,500,000	$1,000,000-750,000
Cost Per Ton		$32 - $24

Total Vermicomposting Costs

Total costs of vermicomposting 100 tpd of municipal solid waste, taking into account potential product revenues, are about $750,000 to $1,000,000/yr or approximately $24 to $32/ton processed.

Gaddie has estimated total conversion time at 70 days, rather than the 110 days used in this report. To examine the sensitivity of this design parameter on costs, the costs of vermicomposting were also calculated assuming a requirement for only about 65 percent of the area used previously. Under these conditions, total annual costs for vermicomposting might decrease from $520,000 to about $400,000, reducing the net cost after revenues to $20 to $28/ton.

COMPARISON WITH ALTERNATIVE METHODS OF MUNICIPAL SOLID WASTE MANAGEMENT

Landfill Disposal

For a municipality of 50,000, the most common method of solid-waste management is a sanitary landfill. Table 6 shows the estimated costs of landfilling. Site acquisition costs are $560,000, based on 112 acres at $5,000/acre. Total site development costs are $760,000 and are based on a 20-yr site life. Equipment requirements are $150,000 for a track loader. The equivalent annual cost of $21,000 takes into account a 10-yr service life and purchase of a second loader in 10 yr. Total capital costs are about $1,500,000, or about $130,000/yr.

Operating costs include labor, fuel and utilities. Two operators are required for the landfill operation. Fuel costs are based on an average loader operation of 7 hr/day, 312 days per year. Total operating costs are about $60,000.

Total annual costs for landfilling are about $190,000, or $6 per ton processed.

Combustion in Modular Combustion Units

Another method of solid-waste management for small communities is combustion in modular combustion units (MCUs). Costs are presented in Table 7. Site acquisition is based on four acres for the MCU facility and 16 acres for the landfill required for ash disposal. Approximately $410,000 is required to develop the MCU and landfill sites. The MCU structure, including receiving building, costs $1,350,000. Costs for the modular combustion unit are $2,110,000 and include the boiler, feedwater treatment equipment and the steam supply line. Landfill equipment includes a track loader ($150,000) and haul truck ($50,000). Total capital costs are about $4,200,000, or an equivalent annual cost of $400,000.

Table 6

COSTS OF LANDFILLING MUNICIPAL SOLID WASTES FOR A
100-TPD FACILITY*

Capital Costs	Cost	Service Life	Amortization Factor	Annual Cost
Site Acquisition	$560,000	-	0.070	$39,000
Site Development	760,000	20	0.094	71,000
Equipment	150,000	10	0.142	21,000
Subtotal (Rounded)	$1,500,000			$130,000
Operating Costs				
Labor				30,000
Fuel				20,000
Utilities				2,000
Maintenance				10,000
Subtotal (Rounded)				$60,000
Total (Rounded)	$1,470,000			$190,000
Cost Per Ton (Rounded)				$6.00

*Reference 24, 25, 26

Table 7

COSTS OF COMBUSTION OF MUNICIPAL SOLID WASTES IN MODULAR COMBUSTION UNITS (MCUs) FOR A 100-TPD FACILITY*

Capital Costs	Cost	Service Life	Amortization Factor	Annual Cost
Site Acquisition	$ 100,000	-	0.070	$ 7,000
MCU Site Development	220,000	20	0.094	21,000
Landfill Site Development	190,000	20	0.094	18,000
MCU Structure	1,350,000	20	0.094	127,000
MCU	2,110,000	20	0.094	200,000
Landfill Equipment	200,000	10	0.142	28,000
Subtotal (Rounded)	$4,200,000			$400,000
Operating Costs				
Labor				240,000
Fuel				80,000
Utilities				25,000
Maintenance				35,000
Subtotal (Rounded)				$380,000
Total	$4,200,000			$780,000
Revenue from Sale of Steam				$300,000
Net Cost				$480,000
Cost Per Ton (Rounded)				$15.00

*Reference: 28

Operating costs include labor, fuel, utilities and maintenance. Total labor costs are $240,000 and based on two-shift operation of the MCU facility (11 persons) and labor for the landfill operation (one person). Fuel costs are $60,000 for combustion and $20,000 for landfill equipment. Utility costs, including power and water, are $25,000. Maintenance of the MCU and equipment for hauling and landfilling ash costs approximately $35,000/yr.

Total operating costs are $380,000/yr, or $780,000 including amortized capital costs.

An MCU unit would probably not be used without a long-term market for steam. Revenues from sale of steam produced in the MCU is based on 9 million BTUs per ton of refuse and 5,500 lb of steam produced per ton burned. Annual steam sales of $300,000 are based on availability of an adjacent steam market.

Total system costs, including credit for revenues, are $480,000 per year, or approximately $15/ton.

Windrow Composting

Although technically proven, commercial composting operations have not been economically attractive in the United States. During the 1950s and 1960s, there were about 20 solid waste composting facilities in operation (30). Nearly all were closed because of high operating costs. For this report, the costs of composting are based on the windrow method, which was operated successfully for several years by the U.S. Public Health Service at Johnson City, Tennessee.

The typical composting facility includes three components: preprocessing, composting, and landfilling of solid waste residue. The solid waste is received, shredded, and then separated by either an air classifier or trommel screen. This scheme is based on an EPA report evaluating small-scale and low technology resource recovery study (31). The heavy fraction is conveyed to ferrous removal and the residue is landfilled. The light fraction is windrowed for about eight weeks in a 4-acre composting area. The loading rate is about 12.5 tons/acre/day. A windrow composting machine is used to periodically turn the windrows. A 2-week curing step follows composting. About one additional acre of land is required for curing. The compost produced is a humus-like material which can enhance the quality of soil.

Table 8 shows the estimated costs for a 100-tpd windrow composting facility. Site acquisition and development costs are about $1,250,000 and include area for a preprocessing facility, a 5-acre paved facility and development of a landfill. Landfill development costs are slightly higher for composting compared to vermicomposting because more residue is produced (42 tpd versus 31 tpd). Costs for structures ($800,000) are for preprocessing facilities and include areas for receiving, shredding, separation and

Table 8

COSTS OF WINDROW COMPOSTING FOR A 100-TPD FACILITY

Capital Costs	Cost	Service Life	Amortization Factor	Annual Cost
Site Acquisition and Development	$1,250,000	-	0.07	$ 88,000
Structures	800,000	20	0.094	75,000
Equipment	1,600,000	10	0.142	227,000
Totals (Rounded)	$3,700,000			$390,000
Operating Costs				
Labor				300,000
Maintenance				110,000
Power				40,000
Fuel				100,000
Sub-Total				550,000
Totals (Rounded)	$3,700,000			$940,000
Revenue				
Ferris Metals				75 - 125,000
Compost				0 - 80,000
Net Cost (Rounded)	$3,700,000			$74,000 - $870,000
Cost per Ton (Rounded)				$24 - $28

ferrous removal; they are about the same as for vermicomposting. Equipment costs are the same as for vermicomposting with the addition of a separation device and a mobil composting machine. Total equipment costs are $1,600,000. Total capital costs are approximately $3,700,000, or an equivalent annual cost of $390,000.

Operating costs include labor, maintenance, power and fuel. Labor costs are approximately $300,000/yr and include preprocessing, composting and landfilling. Maintenance and fuel costs are for operating the preprocessing equipment and mobil equipment such as loaders and trucks. Power costs are principally for operation of the preprocessing equipment and total about $40,000. Total annual operating costs are $550,000.

Total annual costs including amortized capital plus operation are $940,000. Expected revenues for a composting facility are for sale of ferrous metals and compost. Based on the assumptions presented earlier, the annual revenue for ferrous metals is between $75,000 and $125,000. Reliable estimates do not exist for the selling price of a compost product. For this report, the value of the compost has been set at a range of $0 to $5/ton, or approximately its value as a topsoil substitute. Based on a production of about 16,000 ton/yr, the revenue could be up to $80,000/yr. Net costs for composting are $740,000 to $870,000/day, or approximately $24 to $28/ton processed.

Summary of Alternatives' Costs

Unit costs for management of 100 tpd of municipal solid waste are summarized below:

Method	Approximate net cost ($/ton)
Sanitary Landfill	6
Modular Combustion Unit	15
Windrow Composting	24-28
Vermicomposting	24-32

For municipalities with sufficient available, appropriate land, a sanitary landfill is the most economical method of solid-waste management. Windrow composting was found to cost about the same as vermicomposting. In this analysis, modular combustion units were found to cost 2 1/2 times as much as a landfill. Where landfill sites are difficult to obtain and where an energy market exists, however, an MCU might be selected.

Based on this analysis, vermicomposting is not competitive with the other two methods of solid-waste management. Even with the maximum projected market for recovered products, the cost of vermicomposting is four times the cost of landfilling. Vermicomposting becomes competitive with other methods only when a shredded waste is available at no cost to the operator. In that case, the cost of vermicomposting and residue disposal would be about $9 to $17 per ton.

ECONOMICS OF VERMICOMPOSTING A PORTION OF THE WASTES OF A 1,200-TPD RDF FACILITY

We have considered vermicomposting as a potential alternative in solid-waste management for a metropolitan area of 500,000 persons. To make the alternative as attractive as is reasonable, we have assumed that the municipality already owns and operates a facility that is producing refuse-derived fuel from some 1,200 tpd of solid waste and burning the total amount of RDF. Vermicomposting would be conducted as a side operation of 100 tpd of the total 1,200-tpd waste stream.

The 1,200-tpd combustion facility, including RDF preparation, would have a net annual cost of $7,600,000, or about $20/ton processed. This net cost includes a credit for energy recovery in the form of electricity, steam and ferrous metals. The facility would require location in a large urban area due to the quantity of refuse required, while also requiring a large and reliable energy and materials market.

In Table 9, we show the cost difference for vermicomposting obtained when 100 tpd of the total waste stream is diverted to vermicomposting (as before, ferrous recovery would have removed some 8 tpd of the diverted wastes, leaving 92 tpd of processed wastes for vermicomposting). Capital costs for site acquisition, combustion and energy recovery, and residue disposal would remain the same, since the full 1,200-tpd processing capacity is assumed to have been constructed and in operation. An additional $100,000 would be required in order to install conveyors in the preprocessing area to divert the 100 tpd to vermicomposting.

Capital costs of the 100-tpd (92-tpd actual) vermicomposting operation are $3,150,000, as shown in Table 3. The total increase in capital costs above that of a 1,200-tpd RDF facility is $3,250,000, or about $325,000/yr.

Operating costs associated with preprocessing remain the same, since the total waste stream of 1,200 tpd would be subjected to preprocessing. Combustion costs would decrease by $280,000, however, since only 1,100 tpd would be combusted. Residue-disposal costs would remain approximately the same. Vermicomposting operating costs as shown in Table 3 are $210,000. The net operating costs for vermicomposting would be $70,000 less than for the full 1,200-tpd combustion facility.

Including amortized capital costs, increased annual costs, resulting from the vermicomposting side operation, would total about $255,000.

Table 9

COST DIFFERENCE FOR DIVERTING 100 TPD TO VERMICOMPOSTING
FROM A 1,200-TPD RDF FACILITY

Capital Costs	Cost Difference	Annual Cost Difference
Site Acquisition	0	0
Preprocessing RDF	$ 100,000	$ 14,000
Combustion and Energy Recovery	0	0
Residue Disposal	0	0
Vermicomposting	3,150,000	310,000
Subtotal	$3,250,000	$324,000
Operating Costs		
Preprocessing RDF		0
Combustion and Energy Recovery		(-)280,000
Residue Disposal		0
Vermicomposting		210,000
Subtotal		(-)$70,000
Total		$254,000
Revenue: (Sale of castings and ferrous metals for diverted wastes)		(-)$325,000
(Loss of electricity, steam and ferrous revenues in RDF Facility)		$510,000
Net Total Increase In Costs For Vermicomposting		$439,000

Revenues from sales of products should also be considered, however. As was shown in Table 5, sales of castings and ferrous metals associated with the 100-tpd composting system might total $325,000/yr. At the same time, however, yearly revenues of $510,000 from sale of steam and electricity generated at the RDF facility would be lost because of the diversion of 100 tpd to vermicomposting.

Considering total costs and revenues, a combination of combustion and vermicomposting would cost about $440,000 more per year than combustion alone. A municipality owning a large RDF facility would not find it economical to build and operate a parallel or back-up vermicomposting facility.

SECTION 5

VERMICOMPOSTING PRODUCTS AND PRODUCT MARKETING

INTRODUCTION

Successful techniques of vermiculture, including vermicomposting, produce castings and earthworms. Potential markets exist for both products; it has been suggested that income derived from the sale of vermicomposting byproducts can help to offset process costs.

Markets for earthworms can be divided between markets for live earthworms (bait for sports fishing, agricultural uses) and those for dried or processed earthworms (soil additive, animal feed, high-protein diet supplement for humans). Castings have been marketed successfully as a component in potting mixes for horticulture and have been distributed in bulk for land application.

Recognition of the growth of vermiculture among private entrepreneurs prompted the California State Legislature in 1978 to define vermiculture byproducts as an agricultural commodity entitled to the market promotion and safeguards and product-research provisions contained in the California Agricultural Code under the Marketing Act of 1937. Specifically, the legislation states that vermiculture, commercial processing, packaging, sale and use of its byproducts is considered a branch of the state agriculture industry. Consumer safeguards include state regulations governing contracts, establishing requirements for sellers, and allowing purchasers to cancel orders for any reason within three business days. The California Farm Bureau has taken an active role in development and support of vermiculture enterprises, through conduct of discussion on industry research and regulations (J.W. Field, State of California Department of Food and Agriculture, personal communication).

Similar legislation was enacted in 1979 in the State of Washington. Several states have used their securities laws and consumer divisions to regulate the sale of earthworms as breeding stocks. The federal government has no specific vermiculture regulations.

WORM CASTINGS AS A PRODUCT

Castings have obvious agricultural and horticultural appeal, representing, as they do, a natural, "organic" soil amendment with attractive structural properties and low-order plant nutrient values. The castings have a favorable appearance: they lack the offensive odor of wastes (although they might not be entirely odor-free), and, when sifted and dry, they are granular, 0.5 to 2.5 mm in diameter, and of a brownish-gray color.

Passage of organics through the earthworm's gut significantly alters the physical structure of the material. Large particles are broken down into numerous smaller particles, with a resultant enormous increase in surface area (18). As a result of the increase in surface area, any remaining odor-producing sulfides are completely oxidized, microbial respiration is accelerated by a factor of 3, and Salmonella bacteria are destroyed at a higher rate (15, 22).

Remarkable claims have been made for some characteristics of worm castings, including greatly accelerated humification and formation of water-stable aggregates. Results of more rigorous research show, however, that these characteristics pertain more to castings produced by such species as Lumbricus terrestris and Allolobophora longa than to those produced by vermicomposting worms.

Agricultural Value

Castings can act beneficially as a slow-release, low-order nitrogen fertilizer. The actual suitability of castings for agricultural use, however, depends on the composition of the original waste. For example, castings derived from an aged, anaerobic, wastewater-treatment plant sludge in San Jose, California, were found by an independent laboratory to be acceptable for use as a soil amendment in terms of nutrients and salinity, sodium and pH values, but excesses of boron and, possibly, of phosphorus rendered the material unsuitable for direct use as a planting soil (32). Analysis of castings derived from a wide variety of feeds showed most contained amounts of sodium or other salts that would be detrimental to plant growth (33). To date, no specific analysis is available for castings derived from vermicomposting of municipal solid wastes.

Although castings are not generally suitable for use as a sole-source planting medium, mixture of castings with other materials can yield an acceptable potting soil. The laboratory analyzing the San Jose product recommended that castings be incorporated into top layers of agricultural soils, in bulk, or be mixed in specified proportions with sphagnum peat moss, Perlite, potassium nitrate, calcium carbonate lime, and iron sulfate for use as a potting soil, provided that concentrations of heavy metals were found to lie within acceptable ranges. Other worm growers have used different mixes; for example, a 1:1:1 mix of castings, peat moss and Perlite (34).

Anticipated Market Development

The existing or potential markets for castings include:

- o Use as an ingredient in potting mixtures
- o Sale or distribution as an organic soil amendment
- o Sale as an organic fertilizer.

The first of these markets has some potential, at least on a local or regional level. Castings-based potting soils have been successfully marketed in some areas of the United States, including California, Washington, Colorado and Ohio. The castings are usually derived from vermicomposting dairy manure. Consumers have, in fact, shown themselves to be willing to pay a small premium for potting soils that contain earthworm castings, apparently because of good growing performance obtained through use of the product. These operations are very small, however, and there are no available estimates of the volume of castings sold.

The second market is bulk sale or distribution of castings as an agricultural soils' amendment. Competition here would be represented by compost products offered for land application. The advantages of castings over these other products lie in their benign odor and appearance and uniform quality, all of which are consistent with characteristics of other non-sludge fertilizers and amendments currently used in agriculture.

The third market, sale as an organic fertilizer, is not a particularly viable one. In this case, the costs of production are relatively high as compared to those for other fertilizers containing the same or a greater amount of nutrients. In addition, the sale of castings as fertilizer might be constrained by state regulations that define fertilizers in terms of nutrient value. (Arizona, for example, requires that soil additives sold as fertilizer have a nitrogen content of at least 4 percent. The material is also subject to a tax of $0.20/dry ton.) Castings derived from wastes have a nitrogen (N) content about equal to the original waste material N content. For wastewater sludge this may vary from 3 to 5 percent. For municipal solid waste the nitrogen content would be below 1 percent.

Whether sold as a fertilizer or soil amendment or distributed in bulk for application to public lands or farmlands, castings must satisfy the same criteria as other wastes that are proposed for land application (35). Passage of wastes through the earthworm's gut and its subsequent mineralization increase the concentrations of heavy metals or other constituents that might be present in the original wastes. Some of these metals may be accumulated by organisms in the food chain to levels that might be harmful to humans. The waste source must not, therefore, be heavily contaminated by potentially toxic substances. The federal regulations differentiate between crops for human consumption and non-food chain uses, such as use on ornamentals. Most concentrations of heavy metals should not present a problem with application to ornamentals.

EARTHWORMS AS A PRODUCT

According to a report prepared by the University of California Cooperative Extension, "the major use of earthworms today is as bait for freshwater sport fishing...Some worms are also sold to home and organic gardening enthusiasts for soil improvement and composting of organic refuse" (36). Entrepreneurs in the vermiculture industry have made claims for a virtually unlimited market serving the following sectors:

- o Sport fishing (36)
- o Inoculation of horticultural (14) or agricultural soils or reclaimed lands (8, 13)
- o Fertilizer or soil supplement (37)
- o Animal feed (38)
- o Worm stock for vermiculturists (8, 13)
- o Human nutrition (14, 39).

Of these market sectors, the only "large stable market" for vermiculturists, at present, involves sale of baitworms (40). The remaining sectors must be described as speculative, at best. For vermicomposting operations, additional constraints operate, as discussed below.

Recreational Market

L. rubellus and E. foetida are reported to be satisfactory baitworms, but both are rather small -- particularly when raised under high-density conditions of composting -- and so are rather difficult to handle. Some anglers consider nightcrawlers -- not a "domesticated" species -- to be superior baitworms (8, 41), due primarily to their larger size.

Nationally, the market for worms used as bait by sport fishermen has been estimated variously at $5 million (McNelly, personal communication), $26 million (8), $50 million (41, 42), and $80 million (13). The U.S. Department of Agriculture (USDA) has made no objective analysis or projection of the baitworm market, nor has it played any role in regulating or promoting the market (Mr. J. Schwartz, USDA, Beltsville, Maryland, personal communication).

It is difficult to make a valid analysis of the market, because much of the local demand is filled by youthful entrepreneurs selling collected nightcrawlers at roadside stands and by small-scale growers. Other segments of this market are handled through mail order by large-scale growers and wholesalers selling in bulk to retail outlets such as bait shops, tackle shops and fishing resorts.

Retail prices for baitworms range from $1.25 per hundred to $0.50 per dozen, depending on area and the local supply of baitworms. Some retail enterprises reportedly rely on vending machines placed in strategic locations near fishing centers (13).

The University of California Cooperative Extension notes that on occasion the established "local markets have become saturated" by the entry of new worm growers into the business (40).

Beyond the constraint posed by lack of market capacity, distribution of live earthworms that have been raised in wastes could pose public health hazards through exposure of buyers to pathogens contained in or on the worms' bodies or in the substrate. Although this problem might be solved by keeping market-ready worms in a clean substrate for a period of time prior to sale (as is done in shellfish depuration), the added cost of this step, even if feasible, would affect the competitiveness of the waste-raised worms in the baitworm market. No studies are available that indicate the level of pathogenic organisms in earthworms raised in wastes.

Inoculation of Soils

The USDA is on record with the view that earthworms are indicators -- and not agents -- of good agricultural soil. The University of California does not recommend use of earthworms for soil improvement "because we do not know of research data which substantiate claims sometimes made for this" (40). And, although industry sources claim this market "is so large and varied that it is almost impossible to list and discuss," these sources are unable to give even an approximation of its value (13).

Even if a market were available, the demand could not be addressed by a vermicomposting operation. The vermicomposting species E. foetida and L. rubellus are suited only to life in soils containing a very high percentage of organic material. Placed in agricultural soils, these worms are unlikely to survive more than one season (8); their activity during this season is unlikely to improve plant growth (43). Incorporation of both substrate and worms into farm soils might provide a sufficient organic base to extend the worms' useful lifespan somewhat, but this practice would be subject to the same regulatory constraints as apply to land application of any waste. Since the worms would provide no benefit that could not be provided by indigenous populations of the same or different species, the higher cost and management requirements for implanting worms would appear to be unjustified.

Fertilizer or Soil Supplement

It has been projected that conversion by worms of the nation's 16 million tons of wastewater sludge and 120 million tons of municipal refuse produced annually would yield a byproduct of dehydrated earthworms totaling 150,000 tons of 10-percent nitrogen material (37). The economics of the worm market, however, argue against the use of dried worms as a high-nitrogen fertilizer or soil additive. Worms are currently selling at approximately $2.50/lb, wholesale. As worms are more than 80 percent water by weight, more than 5 lb of live worms would be required to produce 1 lb of dehydrated worms. A 5-lb bag of 10-1-1 fertilizer from dried earthworms would cost the wholesaler $62.50. Even in poor market conditions, vermiculturists can find more realistic -- if limited -- markets in sale of live worms to other breeders, organic gardeners, and sport fishermen.

As for the vermicomposting operation, it seems unlikely that worms would be available in such excess as to justify wasting of worm stock for use as a nitrogen additive.

Worm Stock for Vermiculturists

Vermiculturists consider this market to be second only to the fishbait market in its potential (8, 13). Assuredly, it is a market that has served some entrepreneurs well; however, some practices in this market have been legally questionable and have cast a shadow on the larger industry. "Buy-back" arrangements, in which large distributors sell starter packages to home growers with agreement to purchase all worms produced, have often been violated, resulting in large financial losses to buyers and the shutting down of worm-distribution operations in several states (including Florida, Oregon, Wisconsin, Colorado, and California). Buy-back agreements with fixed-price guarantees (sometimes referred to as "binning") are subject to regulation by the U.S. Securities and Exchange Commission (13).

Earthworm stock is not a viable market for other vermicomposting operations, due in part to the potential transmission of disease by pathogenic bacteria and viruses adsorbed onto worms that are raised in wastes. Although the magnitude of this problem has not been documented, some have speculated that the sale of cocoons, rather than live worms, might be feasible (44, 45). Potential advantages of this approach include the light weight, longevity under proper storage, and relative hardiness of cocoons (as compared to earthworms) and the possibility that external surfaces of cocoons could be disinfected by low heat or air drying without harming the developing worms inside. These techniques have not been developed, however, and they may or may not be needed for earthworms raised in municipal solid wastes.

No reliable estimate has been made of market potential for the sale of either worms or cocoons to other growers, although those in the industry claim that demand exceeds supply.

Typical 1974 prices (13) are as follows:

- Breeder stock -- $6.50 to $18 per 1,000 with discounts up to 80 percent in quantities of 50,000 or over

- Bed-run (mixed sizes) stock -- $5.50 to $12 per 1,000 with discounts up to 80 percent in quantities of 25,000 and over

- o Established beds -- $100 to $300 each with no contractual (buy-back) agreement, $350 to $600 each with a contractual agreement.

These prices appear to be in line with current prices. No reliable analysis has been made of market potential; there is a likelihood that entry of a few major new cocoon or worm suppliers would swamp the market and might drastically reduce prices.

Animal Feed or Human Nutrition

The composition of E. foetida is high in protein, as shown in Table 10. A comparative analysis of amino-acid composition in worm meal and commercial-grade meat meal and fish meal, as shown in Table 11, indicates that "the earthworm product has a relatively high level of the essential amino acids, particularly the important sulphur-containing ones (cysteine and methionine)" (39).

Table 10

COMPOSITION OF EISENIA FOETIDA*

Dry matter (%)	20-25
Composition of dry matter (worm meal)	
Crude protein (% Kjeldahl Nx6.25)	62-64
True protein (%)	60-61
Fat (%)	7-10
Ash (%)	8-10
Calcium (%)	0.55
Phosphorus (%)	1.00
Gross Energy (Kcal/Kg)	3900-4100

*From Reference 39

Table 11

AMINO ACID ANALYSES (%) OF HIGH-PROTEIN MEALS*

	Worm Meal	Meat Meal	Fish Meal
Arginine†	4.1	3.5	3.9
Cysteine	2.3	1.1	0.8
Glycine	2.9	7.1	4.4
Histidine†	1.6	1.0	1.5
Isoleucine†	2.6	1.3	3.6
Leucine†	4.8	3.5	5.1
Lysine†	4.3	3.1	6.4
Methionine†	2.2	1.5	1.8
Phenylalanine†	2.3	2.2	2.6
Serine	2.9	2.2	-
Threonine†	3.0	1.8	2.8
Tyrosine	1.4	1.3	1.8
Valine†	3.0	2.2	3.5
Crude protein	61.0	51.0	60.9

*From Reference 39
†Essential amino acids in nutrition, as higher vertebrates cannot synthesize these from nitrogen sources.

Worm meal can be prepared by washing worms clean and then freeze-drying or low-temperature hot-air drying the worms (39). Two University of Georgia researchers have found that dried earthworm meal was palatable to domestic cats (17). Earthworm meal has been compared to meat meal in small-scale feeding experiments on broiler chickens, and to meat meal and a commercial preparation in an experiment with weanling pigs. In both cases, animals raised on worm meal showed no ill effects and, in fact, grew as rapidly as those raised on the more conventional diets. In addition, the broilers gained weight as rapidly on the worm-meal diet while consuming 13 percent less food (39). To date, there has been no federal regulation of earthworm meal.

Those in the vermiculture industry who have investigated this market (44) report that, in order to be competitive, worm meal must be priced in or near the range of $0.10/lb (1979 prices for meat and bone meal) to $0.17/lb (for fish meal). Current wholesale worm prices are two orders of magnitude higher.

The USDA reports no current use of worm meal as a feed product, either for livestock or for pet food. The University of California Cooperative Extension, in its 1978 investigation of worm markets (40), could identify no markets for use as animal feed. The California Department of Fish and

Game reported to the Extension that fish farmers use pelleted food -- and not earthworms -- to feed fish. In the literature, at least one vermicomposting operation in Japan is providing worm meal to fish farmers. Other sources of protein meal, including soybeans, are known to be less expensive than worm meal (13).

The same market constraints as are reported for other uses of live worms apply to the feed market. The presence of pathogens in the waste substrate and adsorbed onto the surface of the worms, the accumulation or concentration of certain heavy metals in worm body tissue, and the fact that earthworms are known intermediate hosts and passive agents in transmission of parasites to poultry, swine and small mammals (11) -- all make it essential that distribution, sale and use of waste-raised earthworms be regulated and monitored. Steps used in processing of worm products could control transmission of biological agents, but only source-control measures and limits on worm residence time in wastes could prevent excessive accumulation of heavy metals in worm tissues.

MARKET PROSPECTS

Most markets that have been proposed for castings and worms appear to be severely limited by lack of market demand and by potential public-health considerations that must be addressed in distributing any waste-derived product. The nutrient value of castings, however, and their aesthetic and handling characteristics make them a desirable agricultural soils amendment. Provided that the waste from which the castings are derived is relatively "clean" in terms of heavy metals and other toxics and provided that pathogen removal can be demonstrated (or developed) as part of the vermicomposting process, castings have the potential of filling local or regional demand for a low-order fertilizer and soils amendment. The material could be mixed with other potting materials for sale as a planting medium, bagged for wholesale distribution, or stockpiled for pickup by local gardeners and farmers.

Although prospects are undefined for product income offsetting production costs, this market would serve, at the very least, to reduce a municipality's current costs for disposal of municipal solid wastes.

SECTION 6

ENVIRONMENTAL AND PUBLIC HEALTH ASPECTS OF VERMICOMPOSTING

There are two major areas of concern in the selection of vermicomposting as a municipal solid waste management technique: potential on-site problems at the vermicomposting facilities, and potential risks in the use of vermicomposting products.

POTENTIAL ON-SITE PROBLEMS

A vermicomposting facility must comply with Environmental Protection Agency "Criteria for Classification of Solid Waste Disposal Facilities and Practices," regulations that were issued in September 1979 as an implementation of Subtitle D of the Resource Conservation and Recovery Act (RCRA). The regulations contain criteria for determining what solid-waste practices pose potential adverse effects on health or the environment. Impacts on floodplains, endangered species, surface waters, groundwater, food-chain croplands, disease, and safety are discussed; several of these factors are of importance in assessing the environmental and public-health aspects of vermicomposting.

Site Runoff and Leachate

Possible site runoff and leachate pose threats to both surface and groundwaters. In order to protect off-site surface waters, rainfall runoff should be diverted around the site by means of a simple drainage system. On-site runoff should be collected for discharge to sewers or be stored in holding tanks or ponds for later disposal to sewers or for separate treatment. The magnitude of on-site runoff can be controlled by limiting irrigation to the minimum required.

Most precipitation will be absorbed by the windrows of relatively dry municipal solid waste; in fact, wastes can be expected to have a moisture content of about 30 percent and so need to be moistened to about 50 to 60 percent to initiate composting. Up to 15,000 gal/day of water may be required for irrigation at a 100-tpd facility.

Another major concern is prevention of the infiltration of polluting nutrients or toxic materials into groundwater supplies. The RCRC regulation prohibits any contaminant levels in groundwater that exceed the

National Interim Primary Drinking Water Regulation standards, which include inorganic and organic chemicals, coliform bacteria and radioactivity. Leachate can be controlled either by selecting a facility site that is underlain by an impervious soil layer or by installing an underlying impervious layer of soil or synthetic material.

Disease Vectors

A vermicomposting facility should be designed to minimize the on-site population of rodents, flies and mosquitoes capable of transmitting disease to humans. At the facility visited during this study, disease vectors were not a problem and have not reported to be a problem at other installations.

Adult flies and fly larvae and pupae are brought into the facility with the solid waste. However, temperatures reached during the thermophilic composting phase are lethal to fly larvae and eggs (46). A properly operated vermicomposting operation would be preceeded by a period of windrow composting.

Protective fences have been used at some sludge vermicomposting facilities to prevent predation by ground squirrels, moles, armadillos and birds, all of which eat worms. One vermicomposting operator notes that small animals have caused no severe problems at his operation, despite the fact that it is located near a wildlife sanctuary (47).

Although birds have not been cited as a problem at most vermicomposting facilities, it seems likely that at a large facility (as at most landfill sites) their population would increase. Some earthworm loss might be expected.

Safety

Safety is of concern to both the public-at-large and to on-site workers. The RCRA regulations require that entry to the facility be controlled in order to minimize the exposure of the public to hazards of heavy equipment and exposed wastes.

Safety hazards to facility operating personnel will be similar to safety plans applicable to other municipal solid waste disposal facilities and can be reduced through proper training, use of safety equipment, and other practices. At a vermicomposting facility, the greatest hazard is in preprocessing equipment and where mobil equipment is being operated.

Odors

Vermicomposting operations require aerobic -- and, therefore, relatively odor-free -- conditions. The use of vermicomposting techniques that hasten conversion of waste into castings will virtually eliminate any odor nuisance; castings have no objectionable odor and apparently will not develop odors even when stored for a period of time under adverse conditions. In a test directed by the Texas Department of Water Resources and conducted by the Angelina & Neches River Authority of Texas, worm castings were sealed in an air-tight jar and maintained at 70°F. At the end of seven days, the seal was broken, and tests were made for the presence of odors, hydrogen sulfide, and other indications of anaerobic conditions. The test report states that the only odor detected was a moist earthy smell. There were no indications of hydrogen sulfide or anaerobic conditions (48). No other odor tests on castings have been reported in the literature.

POTENTIAL RISKS IN DISPERSAL OF PRODUCTS

As discussed previously, the vermicomposting operation yields two products -- castings and worms -- for which there are potential markets. Some of these potential markets are constrained by limits on demand, and others, by environmental problems that might result from increased dispersal and application of waste-derived products. Of primary concern among these potential environmental problems are the toxic substances and pathogenic microorganisms that can be present in municipal solid waste. Typical municipal solid waste would be expected to contain between 15 and 20 percent food wastes by weight (49). Most substances of a public health concern would originate in these wastes.

Toxic Substances and Heavy Metals

Use of worm castings as an agricultural soils amendment, landscape "top dressing", or potting soil ingredient represents the most viable potential market for a vermicomposting product. Because the castings are derived from wastes, however, there exists a potential for contamination of the product by heavy metals, chlorinated hydrocarbons and other toxic substances. If dispersal is to non-food chain crops the health hazard would be reduced.

It is not clear whether earthworm consumption changes the availability of metals to plants. According to research reported in Edwards and Lofty (11), the (plant) availability of lead and zinc (and calcium) is increased by worm activity, but Neuhauser has stated that conversion of aerobic sludge to castings neither increased nor decreased plant-available cadmium, copper, nickel, lead and zinc (50). Worms apparently are quite capable of concentrating some heavy metals -- such as cadmium -- to levels high enough to be toxic to birds or small mammals preying on them (51, 52).

Most researchers have found that worms fed sludge accumulate the following heavy metals: cadmium (50, 51, 52, 53, 54), copper (51, 55), nickel (52), mercury (56), zinc (51, 52, 53, 57, 58), and lead (52, 53, 57, 58). Whether this concentration actually occurs in worms feeding on solid waste under conditions of vermicomposting has yet to be determined. Apparently, much depends on the worms' residence time in the substrate, on the water solubility of the metal in the substrate, and on the level of the metal in the substrate.

In addition to heavy metals, a number of other toxic substances can be accumulated or concentrated in worm tissues. Among them are the organochlorine insecticides such as DDT. It is not known to what degree, if at all, the process of vermicomposting hastens degradation of these persistent substances.

Uptake of pesticides by earthworms has been reported to the following levels (11):

DDT and residues	8.0 to 10.6 x soil levels
Aldrin	3.3 x soil levels
Endrin	3.6 x soil levels
Heptachlor	3.0 x soil levels
Chlordane	4.0 x soil levels

The worms' uptake of DDT is relatively rapid; at a concentration of 1 ppm in the substrate, worms will reach background levels within nine weeks (11). Organophosphorus insecticides, such as parathion, do not appear to be concentrated by worms (11).

No studies are available on accumulation of substances during vermicomposting of municipal solid waste. The results of the sludge studies show the general direction, but because solid waste is expected to have lower concentrations of these substances, the potential risk in dispersal of the product is likely to be much lower.

Pathogens

Municipal solid wastes undergo a composting phase before the wastes are vermicomposted. Studies of municipal refuse composting at Johnson City, Tennessee, showed a significant reduction in coliform bacteria levels. However, significant regrowth occurred when temperatures dropped during the last stages of composting. Regrowth might also occur during the relatively moist and aerobic conditions during vermicomposting.

No studies are available on the pathogens before and after vermicomposting of municipal solid wastes, however, the Texas Department of Health found no *Salmonella* in sludge-derived castings or in live earthworms used in a Shelbyville vermicomposting operation. At one time, the Shelbyville facility was vermicomposting raw sludge obtained from the Center, Texas, wastewater treatment facility (48).

Since very little is known about pathogens remaining in castings, it might be necessary to establish specific conditions of vermicomposting such as maintenance of a defined "curing" period for castings, before the castings could be used.

Several vermicomposting operators have suggested that castings might also be sterilized by steam treatment, open-flame heating, or exposure to 100 percent methyl bromide gas, but the efficacy of any of these methods is not known.

SUMMARY

Potential on-site problems in vermicomposting include runoff and leachate, the presence of disease vectors, odors, and worker safety. None of these problems should be present in a well-designed and operated vermicomposting facility.

It is likely that vermicomposting facilities will rely on sale of castings to offset a portion of operating costs. There is a risk associated with the dispersal of castings which may contain heavy metals and pathogens. The presence of these substances and organisms has been documented for castings derived from municipal wastewater sludge. No data is available for solid waste vermicomposting, however. The relative hazard to public health needs to be documented.

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16. ABSTRACT

Vermicomposting of municipal solid wastes has been attempted only in the last five years and there are presently no full-scale operations. This report assesses the technical and economic feasibility of vermicomposting and is based on several pilot-scale studies conducted by private entrepreneurs.

The assessment is based on examining facilities and costs for a municipal operation serving (1) a community of 50,000 persons and (2) a community of about 500,000 persons. Vermicomposting is compared to three other methods of solid waste management: sanitary landfill, windrow composting, and combustion. Vermicomposting was estimated to cost about $24 to $32 per ton of waste processed. This cost is high compared to most other available methods. Additionally, the market for earthworm castings is not established. Since total process costs, including revenue from sale of products, are central considerations in the selection of a preferred solid waste management option, the typical communities examined in this report have available to them technologies which are more attractive than vermicomposting.

17. KEY WORDS AND DOCUMENT ANALYSIS

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