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ENGINEERING ASSESSMENT OF VERMICOMPOSTING MUNICIPAL WASTEWATER SLUDGES

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ABSTRACT

Vermicomposting -- the biological degradation of organic matter that occurs as earthworms feed on waste materials -- has been advocated by some as a means of stabilizing and disposing of municipal wastewater sludges. Based on review of available literature, discussions with practitioners, and visits to sites where vermicomposting is being attempted on an experimental scale, the process has been found to be feasible and potentially competitive economically with conventional sludge-stabilization techniques such as landspreading of liquid sludge and static-pile composting. The question of whether vermicomposting is the equivalent of conventional processes in stabilizing sludge and reducing pathogens in it remains to be answered at demonstration scale.

In feeding on sludge and defecating undigested remains as "castings", worms alter the physical structure of the sludge, changing it in composition from an amorphous mass to small discrete particles. The resultant enormous increase in surface area accelerates drying, aeration, and microbial activity. The castings have a faint odor of fresh earth or compost and are quite dry and pebbly in consistency. Because their nutrient value is roughly the equivalent of the sludge from which they were derived, they might be of agricultural benefit if used as a "top dressing" or soils amendment, provided that concentrations of toxic heavy metals in the original sludge were at levels considered acceptable for agricultural use.

Vermicomposting proceeds most rapidly in moist, aerobic conditions, with temperatures maintained within a moderate range of 13°C to 22°C. Anaerobically-digested sludges cannot support a thriving worm population. If liquid sludge is used as a feed, it is necessary to apply it to a bulking agent (such as sawdust) to reduce the substrate's moisture content and assure aerobic conditions. A wide variety of sludge feeds have been used in vermicomposting experiments, but analysis of actual dry solids loading rates at six vermicomposting operations show sludge:worm (S:W) ratios to fall within the relatively narrow range of 0.12 to 0.27 lb dry solids to lb worms per day.

Of the different techniques of vermicomposting currently being used, only vermicomposting of liquid primary and waste activated sludges appears competitive at present stages of development. Vermicomposting of dewatered sludge in raised indoor beds is, at present, too labor-intensive for economical scale-up. Costs for labor alone would be about $300 per ton. Outdoor windrowing techniques are not suitable for year-round use in most areas of the United States. Costs developed for the vermicomposting of liquid sludges in protected facilities are estimated at $105 to $235 per ton,

depending on the type of structures used.

An S:W ratio of 0.20 was assumed for determination of vermicomposting costs. Areal requirements were assumed to follow those generally used in vermiculture, or about 0.4 lb of worms per square foot of bedding. The product of the S:W ratio and areal requirement was found to yield a loading density of 0.08 lbs of sludge per day per square foot of area; this density was used as the basis for developing cost estimates. Loading densities of up to four times this figure have been reported to be successfully used, but feasibility of the higher loadings remains to be demonstrated at full scale.

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Section 1. INTRODUCTION

Purpose of Study

The "Engineering Assessment of Vermicomposting Municipal Wastewater Sludges" is an engineering and scientific feasibility study of vermicomposting as a means of stabilizing, disinfecting and converting municipal sludges to a usable soils amendment. The report contains:

- Discussion of the state-of-the-art of vermicomposting of municipal sludges
- Engineering analysis of the technical and economic aspects of vermicomposting municipal sludges
- Recommendations as to the applicability of vermicomposting to present and future sludge-management needs
- Recommendations for further study

Work was carried out as a work effort (WE-2) under Contract No. 68-03-2803, U.S. Environmental Protection Agency (EPA), Office of Research and Development, Municipal Environmental Research Laboratory. 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 visits to seven sites where vermicomposting of sludge is being practised and/or 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.

Format of Assessment

In successive chapters, this report covers aspects of the vermicomposting process (Section 2) and its facilities (Section 3), vermicomposting products and product marketing (Section 4), environmental and public-health issues (Section 5), economic considerations (Section 6), and findings and recommendations (Section 7). The material presented is based on critical review of the available literature, site inspections, and discussions with those working in the field. As a result of the technical evaluations described in Sections 2 and 3, we have identified two methods of vermicomposting that are currently being practised with a degree of success and have developed in Section 6 a range of unit cost estimates for vermicomposting. The implications of these costs for vermicomposting are among the major findings discussed in Section 7.

Section 2. PROCESS OPERATION

Definition of Vermicomposting

Vermicomposting involves the degradation of organic wastes by earthworm activity. Some species of earthworms (although not the common nightcrawler and garden worm) thrive in managed conditions on a diet and substrate composed almost entirely of organic matter. When these worms are added to shallow beds or windrows of sewage sludge, they will feed on the sludge, digest a portion of the organic matter and expel the undigested remains as feces, or castings.

Breakdown of organic constituents of the sludge inside the worm's gut is followed by continued decomposition of the material after it is defecated. The rate of sludge decomposition is accelerated over what would occur without worm activity, due primarily to the small size of the expelled castings and, therefore, to the greatly increased surface area they offer for exposure to air and attachment by microorganisms.

After the worms have fed on the sludge and converted it into castings, more sludge can be added. Eventually, however, the worms must be separated from the castings and provided with new sources of food. Worms can be recycled into new beds of sludge or, possibly, marketed in some form. The castings, once dried, have properties that might make them a desirable soils amendment. The end products of sludge vermicomposting, therefore, are worms and castings.

Typically, the facilities associated with vermicomposting are of a low order of technology. Beds can be raised or on the ground. Some worm beds might be set aside for propagation of new stock. Protection from weather extremes must be provided. Some means of delivering and spreading sludge should be included, and a technique for separating the products should be arranged (automatic rotary harvesting screens are available, but other methods might be feasible).

Vermicomposting has been compared to static-pile composting of sludge, as developed by U.S. Department of Agriculture (USDA) at Beltsville, Maryland. Although both processes require moist, aerobic conditions, however, they are neither identical nor compatible. Static-pile composting involves degradation of sludge by a wide variety of heat-tolerant bacteria, whose metabolic activity generates appreciable increases in temperature (up to 70°C, at the most active stage). Vermicomposting, on the other hand, depends on the maintenance of moderate temperatures in the range of 13°C to 22°C.

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 practising vermiculture depend heavily on the baitworm market to realize some income from the business.

To our knowledge, only since 1970 has the vermicomposting of wastes been attempted at any more than barnyard scale. Pioneering efforts commonly mentioned in the literature (1, 2) include a demonstration project at Hollands Landing, Ontario (Canada), which was begun in 1970 and has since been operated under private ownership, and a pilot-scale, one-time demonstration of vermicomposting municipal solid waste (MSW), which was conducted in 1975 at Ontario, California. The Hollands Landing facility has vermicomposted small amounts of manure, food-processing wastes, and sludge (Carl Klauck, owner, personal communication); the Ontario, California project involved composting and vermicomposting of nine tons of hand-sorted municipal refuse over a period of 120 days (1).

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 (3). Information obtained through sources in the vermiculture industry indicates, however, that only a handful of privately-owned installations are operating in Japan (as in the United States), the largest of which can process about 30 TPD of pulp and food wastes. Operation appears to be rather labor-intensive, and the economics appear to depend heavily on disposal fees and on sale of freeze-dried worms (as fish feed) and castings (Shizuro Aobuchi, personal communication).

Current Status

At present, vermicomposting is being practised at several installations across the United States. Some of these projects represent funded demonstrations, such as ongoing work being carried out under National Science Foundation grants in San Jose, California and Syracuse, New York. Others -- in Maryland, Washington and Florida, for example -- are being conducted by vermiculture entrepreneurs who are eager to demonstrate the potential of vermicomposting in waste management. And in Texas, the state and the municipality itself are supporting demonstration of vermicomposting sludge at the Lufkin wastewater-treatment plant.

In the course of this investigation, seven vermicomposting operations were visited in order to confirm details of process operation and to view at first hand the techniques and facilities used. The following visits were made between July and October 1979:

Keysville, Maryland -- Vermicomposting in indoor beds of approximately 50 pounds per day (dry solids) of aerobically-digested, concentrated and air-dried sludge.

Louisville, Colorado -- Pilot-scale vermicomposting of composted yard wastes

Lufkin, Texas -- Vermicomposting of 900 pounds per day (dry solids) of thickened primary and waste activated sludge sprayed over sawdust beds

Ridgefield, Washington -- Experimental vermicomposting of aerobically-digested liquid sludge applied to windrows

San Jose, California -- Windrow vermicomposting of sludge that has been dried in a lagoon for several years

Syracuse, New York -- Laboratory-based research into vermicomposting of digested sludges

Titusville, Florida -- Experimental vermicomposting of approximately 140 pounds per day (dry solids) of sludge

Accounts of these site visits are included as the Appendix to this report.

Description of the Process

Sludge Feed

The sludge feed to vermicomposting operations can take a variety of forms, ranging from liquid sludge to sludge cake to dried sludge. To our knowledge, 10 wastewater-treatment plants in the United States are currently contributing a portion of their sludge for use in vermicomposting. Septage (pumpings from septic tanks, in this case dried to 16 percent solids) has reportedly been used for vermicomposting in the Eugene, Oregon area (4).

Researchers at the State University of New York at Syracuse have found that anaerobically digested sludges are unsuitable for vermicomposting (5). If freshly obtained from the digester, the sludge is toxic to worms; if aged for several weeks after digestion, the sludge still fails to support a thriving earthworm population. It is not known what constituent(s) in the anaerobically digested sludge is toxic to worms.

Liquid Sludge. Vermicomposting operations in Ridgefield, Washington and Lufkin, Texas are based on use of liquid sludge. At Ridgefield, aerobically-digested sludge from three wastewater-treatment plants (WWTP) is applied to unprotected windrows in a field (Figures 2-1 and 2-2), while at the Lufkin WWTP, combined primary and waste activated sludges are gravity-thickened to about four-percent solids and pumped to enclosed vermicomposting facilities located onsite (Figure 2-3).

Sludge Cake. At Keysville, Maryland, a pilot-scale vermicomposting operation uses a sludge cake obtained from the New Oxford, Pennsylvania WWTP, where the sludge has been aerobically digested, conditioned with polymers, and dewatered to about 12-percent solids on a belt filter press. The operator then air-dries the sludge to about 18-percent solids before applying it to the vermicomposting beds.

A vacuum-filter cake from another WWTP was formerly used at Keysville. When the method of conditioning sludge at that WWTP was changed from polymers to lime and ferric chloride, however, the sludge was found to be unsuitable for vermicomposting.

In an Akron, Ohio study, raw waste activated sludge was dewatered by centrifuge to approximately 10 percent solids before vermicomposting (6).

Dried Sludge. In San Jose, California, sludge dried in large lagoons to more than 80-percent solids has been shaped into windrows for a vermicomposting demonstration project. The sludge, generated at the San Jose WWTP, was anaerobically digested and dried in the beds for two years or more prior to its use in vermicomposting. The vermicomposting operator found it necessary to rewet the material for a 14-day period before introducing earthworms to the windrows.

Figure 2-1
Repro size 6 x 3
100%

Figure 2-1 Vermicomposting windrows being formed at Ridgefield, Washington

FIGURE 2-2
RERO SIZE 6 x 3½
100%

Figure 2-2 Applying aerobically-digested municipal wastewater sludge to vermicomposting windrows at Ridgefield, Washington

FIGURE 2-3
REPRO SIZE 6 x 3¼
R 70%

Figure 2-3 Structures enclosing vermicomposting facilities adjacent to municipal wastewater-treatment plant, Lufkin, Texas

Requirements for Supplemental Substrate

From the preceding discussion, it is evident that a wide range of sludge processes can be used prior to vermicomposting. Some operators have found sludge alone to provide a suitable substrate for the worms, provided that it can be kept in an aerobic condition and that its moisture content is within the range considered ideal for the worms' feeding (see "Conditions of Culture"). Those installations handling liquid sludge, however, require supplemental substrate in the wormbeds in order to maintain aerobic conditions and ideal moisture content in the vermicomposting mass.

The supplemental substrate can be materials such as sawdust, woodchips, cardboard, other waste products including municipal solid waste, or mineral soil. At Lufkin, Texas, an eight-inch layer of sawdust is used as a bedding material to absorb liquid sludge that is sprayed over it. The Lufkin operators originally started with only 2 to 3 inches of bedding, but increased the depth in order to maintain aerobic conditions and offset consumption of sawdust by earthworms. At some other installations, sludge is mixed with cardboard or other wood byproducts.

A mineral-soils substrate might support the fastest rates of sludge conversion and worm growth (7). Possible reasons given for this include changes in cation exchange capacity, the assistance of the soils in grinding food in the worm's gizzard, and microbial effects -- but these are all somewhat speculative. More research is needed to determine whether such a substrate is needed or whether proper processing of sludge prior to vermicomposting eliminates the need.

Problem Constituents

Some materials in sludge or substrate materials can cause reduced feeding activity among the worms or can have toxic effects on them. Unfortunately, only very limited research has been conducted in this area. Some guidelines for avoiding such problems have been developed in manuals of vermiculture, but the best prevention is said to be 12-hour jar-testing of the material using a small sample of live worms (8). In some cases, leaching of marginal materials -- animal manures, some peat-moss products, and pulp products containing aromatic oils -- will make them suitable for use.

As discussed previously, anaerobic sludges are toxic or harmful to worms. Use of ferric chloride, lime and alum for phosphorus removal and chemical conditioning of sludge can reduce worm activity (Paul France, personal communication). Ammonium salt added as acetate at 1,000 ppm was lethal to worms after two weeks, and copper added as copper sulfate at 2,500 mg/l was lethal to worms within one week (9).

Extremes of pH in either sludge or bedding will be harmful to worms. Pulp obtained from processing coniferous trees can contain resins that will cause worms to migrate out of the beds (8).

A number of synthetic organic chemicals used as agricultural agents can be harmful or toxic at high dosages, according to researchers working on field tests. Fumigants, carbamate fungicides and carbamate insecticides were found to be generally toxic; organophosphate and organochlorine pesticides generally had harmful effects. Most herbicides were not found to have direct harmful effects (10).

For the purposes of this investigation, it can be assumed that aerobic sludges obtained from most facilities treating predominantly domestic wastewater flows will be safe for use in vermicomposting.

Bed Depth and Configuration

Outside of the need to shape wormbeds so that they are fully accessible to operators for maintenance, the principal criterion for bed configuration is based on the absolute requirements for moist, aerobic, moderate-temperature conditions within the beds. These requirements can be met by maximizing the surface-area-to-volume ratio. Shallow beds or windrows provide the greatest exposure of sludge to air, helping to maintain aerobic conditions in the sludge mass, preventing accumulation of excess moisture at depth, and dissipating excess heat generated by microbial decomposition of the sludge. In addition, since the worms used in vermicomposting are found in nature in the uppermost layers of soil, the use of shallow beds conforms to the worms' instincts for vertical distribution.

The best way to maintain optimum vermicomposting conditions year-round is to cover or enclose the wormbeds. At Ridgefield, Washington, vermicomposting is conducted using windrows located out-of-doors. During the winter, however, the earthworms reportedly migrate to lower depths in the ground to protect themselves against freezing; feeding activity is significantly reduced. Other outdoor vermicomposting operations have sustained worm losses from heavy rains (San Jose, California and Akron, Ohio) and hurricane-force winds (Titusville, Florida).

Biological Parameters

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 (5) -- the nightcrawler -- and Allolobophora caliginosa (1) -- the field worm, and these same species often will invade the lower reaches of composting windrows (11), 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 (12, 13).

Not surprisingly, the two worms that 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 that can accompany bacterial decomposition of organic matter (11).

E. foetida is commonly known as the brandling worm (also red worm, red wiggler, manure worm, red-gold hybrid (11)). A relatively small worm of 4 to 8 mm diameter and 100 mm in length (10, 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 it from most other earthworm species. E. foetida can tolerate somewhat higher temperatures than can most of the subsurface, burrowing species (14); 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, 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 2-1 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 when growth began.

Sound experimental techniques will one day resolve these discrepancies and fill in other gaps in our knowledge of earthworm biology as it applies to vermicomposting. In the meantime, it is advisable to use the conservative values, although earthworms entrepreneurs have made a practice of using the outer-limit values to support their claims of high production and growth in their earthworm populations.

Life Cycle in Earthworm Species Used in 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 2-1.

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 located at the "front" end of these worms, somewhat behind the genital pores. (The clitellum secretes the fibrous cocoon, and clitellar gland cells produce a nutritive albuminous fluid contained in the cocoon.) They can 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 (11), and falls off

Table 2-1

BIOLOGICAL DATA ON FOUR SPECIES OF LUMBRICID WORMS*

Characteristic	Vermicomposting Species: Eisenia foetida	Vermicomposting Species: Lumbricus rubellus	Non-Vermicomposting Species: Lumbricus terrestris	Non-Vermicomposting Species: 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

*From (7, 9, 10, 11, 15) and (Neuhauser, personal communication)
**Information not found

directly with decreasing soil temperatures (we have not seen any discussion of 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 measured in only a few days (8) -- most vermiculturists assume population doubling times of 60 to 90 days (11, 16). 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 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.

In general, conditions of heat and drought are more dangerous to earthworms than those of wet and cold. (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.

E. foetida reportedly have lived for more than four years in controlled conditions. In the field, average lifespans probably range from one to three years. Among 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).

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. Table 2-2 illustrates the effect of temperature on feeding rates.

Table 2-2

FEEDING OF EISENIA FOETIDA AT DIFFERENT TEMPERATURES*

Temperature (°C)	Feeding rate** (g dry wt sludge/ g dry wt worm/day)
5	0.132
10	0.434
15	1.699
20	1.526
25	0.876

*From (17)
**As determined by egestion of castings

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; below 4°C, production of cocoons and development of young earthworms cease. Worms will tend to hibernate and move to deeper layers 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 their hatching to adulthood under controlled conditions and 25° temperatures 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 (7, 11). For worms not acclimated to higher temperatures, activity is significantly reduced at 25°, and there may be loss-of-weight and mortality (5, 18).

The unfavorable effect on worms of high (25°C and above) temperatures is not entirely a direct effect. Warm temperatures also support accelerated growth and activity of microorganisms in the substrate; the increased microbial activity tends to use up available oxygen, to the worm's detriment (5).

Although the ultimate goal of sludge processing is the breakdown and recycling of complex constituents in the sludge, the increased microbial catabolism of sludge at higher temperatures probably is not desirable in vermicomposting. Depletion of available oxygen by microorganisms in the substrate will interfere with the worms' activity; the worms' reduced feeding will result in significantly lower turnover of sludge into castings. The signal advantage of vermicomposting is the rapid conversion of sludge to a relatively aerobic, odorless product that can then be decomposed by microbes at rates three times faster (18) than can sludge that has not been digested by worms. The vermicomposting operation should be designed to maintain temperatures within the 13° to 22° range found to be optimum for feeding.

pH. Earthworms generally prefer neutral soils (1), and both E. foetida and L. rubellus find their optimum at pH 7.0 to 8.0, neutral to mildly alkaline (11). 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 (10).

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 (10). Operators can also control acidity by adding lime (19) or limestone flour (8), as necessary.

Moisture Content. Under the right conditions, earthworms have extraordinary capabilities to survive either submersion in water or dehydration. L. rubellus and other worm species have been shown to survive 31 to 50 weeks in total submersion, provided the water is aerated. In fact cocoons were produced and hatched, and young worms fed and grew under water (10). In practical experience, however, worms used in composting have been reported drowned by "exceptionally heavy rains" (6) or to have migrated out of vermicomposting windrows during periods of rain (20). It is likely that the adverse effects are due more to depletion of oxygen in saturated sludge than to the moisture itself.

The threat of drying -- desiccation -- is more serious. Earthworms are up to 85 percent water by weight, and this water is easily lost through the worms' skin and protective outer covering. Worms can lose 75 percent of their moisture content and still survive, provided they are revived immediately by immersion in water.

E. foetida will drive down to deeper soil levels in dry conditions (11). Prolonged drying of composting beds or windrows will result in loss of feeding activity and death of the worms. Every author on vermiculture stresses the need to keep bedding materials moist.

In nature, the greatest number of worms will be found in soils of 12 to 30 percent moisture (11). 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. Sludge that has been dried to less than 50 percent moisture might be too hard for E. foetida to burrow through (5).

The worms' feeding rate apparently is independent of moisture content as long as a threshold value of moisture is present (17).

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 (10). Feeding activity might be reduced (7). E. foetida has 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 (10).

In the vermicomposting operation, aeration requirements can be met by (1) maximizing surface area in the compost beds or piles, (2) protecting against bed saturation, (3) adding bulking agents such as wood chips or sawdust to the beds, (4) maintaining temperatures within the optimum range for feeding, (5) mechanically turning or tilling the beds at regular intervals (say, every two to three weeks.) Some researchers argue against mechanical turning, both because it can cause trauma to the worms and because it can redisperse castings into the substrate, with possibly toxic effects on the worms (7).

Nitrogen and Other Substrate Minerals. Earthworms reportedly thrive in a medium of 9 to 15 percent protein (19). Fresh bovine feces contain about 14 to 15 percent protein (19), sludge can vary from 12 to 38 percent protein, and unsorted mixed municipal refuse may contain only 4.2 percent protein, depending on sources (21). 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 (22). This optimal range corresponds well to that found in most sludges. Only the most biodegradable fractions of municipal solid waste, however -- such as yard wastes and food wastes -- fall within this optimum range; unsorted or processed mixed municipal refuse will have a C:N ratio on the order of 50:1 (21). Application of high-nitrogen fertilizers is not recommended, as these can create unfavorable acidic conditions (11).

A lower threshold for calcium of 800 mg/kg has been shown to permit growth of the field worm, Allolobophora caliginosa. No upper limit is known, and concentrations as high as 3,600 mg/kg have supported growth (11).

Concentrations of potash and phosphorus have not been shown to have a direct effect on worm growth. Soil-surface concentrations of copper of 260 ppm are toxic to earthworms (11). Many industrial and agricultural chemicals are toxic to earthworms, as discussed in a previous section.

Generally speaking, mixing of soil into the substrate appears to promote worm growth and development, perhaps due to inorganic constituents found in soil (22).

Light. Worms have concentrations of light-sensitive cells in their skin, and they will migrate toward weak sources of light, away from strong sources of light (10). Installation of protective shading will not only prevent worms from burrowing deeper into the compost bed, but also help to keep summer temperatures at moderate levels favorable to feeding. (Ideally, the shading can be removed in winter months to take advantage of solar heat.)

Substrate Compaction and Maintenance. The field worm, *A. caliginosa*, has been shown to migrate freely from loose soil into highly compacted soils (23). While compaction itself might not pose problems to worms, failure to keep substrate loose and aerated can kill worms or cause their migration out of the substrate.

Of prime importance, substrate must be replenished before it is exhausted. Worm castings have toxic effects if eaten by the species of worm that produced them, as has been observed in laboratory conditions (7), and worms will migrate from composting beds when adequate food is not available (Collier, personal communication).

Density. Recent laboratory results obtained by Neuhauser *et al* (24) relate worm survival and growth to population density. The findings show that growth rates during the worm's rapid phase of growth (from age three weeks to about 9-12 weeks) are considerably depressed by crowding. At 4 worms per 250 g of centrifuged activated sludge (11% solids) on 50 g of soil, *E. foetida* grew at an average rate of 250 mg per week; at 16 worms in the same 78 cm^2 area, growth fell to 170 mg per week. The effects of crowding are attributed to competition for food, diversion of energy into production of cocoons as opposed to production of body tissue, and to the accumulation of castings, which are toxic to *E. foetida*. The researchers found that activated sludge dewatered to 11-percent solids had a high population carrying capacity; by extrapolation, 2900 g of worms could be supported in one square meter of space if sufficient sludge were present. This biomass would be about 10 times that found in naturally occurring populations (10).

Performance in Vermicomposting

As the worms eat and digest sludge, they expel the digested material as "castings", which are nothing more than worm feces. Castings, lying next to uneaten sludge, are immediately distinguishable: the large particles, irregular shapes or amorphous surfaces of sludge 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 0.5 mm in diameter and 1.0 mm in length (25). Their odor is that of fresh earth or compost and is not noticeable unless an effort is made to smell the castings close up. Because of their relatively uniform shape and size, castings can be considered aesthetically superior to many other sludge products.

Rates of Vermicomposting

The rate of biological decomposition is controlled by two variables: (1) the feeding rate of the individual organisms and (2) their density. The product of these two values provides sizing criteria for rate of substrate decomposition per unit volume or unit area.

In vermicomposting, a logical expression for feeding rate would be dry weight of sludge consumed per day per unit weight of worms. This feeding ratio can be expressed as follows:

$$\frac{\text{(Dry weight of sludge)}}{\text{(Wet weight of worm) (Days to total conversion)}} \qquad (1)$$

We have termed this ratio the sludge-worm ratio, or S:W ratio. The S:W ratio can be applied to any vermicomposting operation, regardless of the moisture content of the sludge received or of the depth to which sludge is applied.

In some biological systems, such as in the activated-sludge process, the density of organisms is measured per unit volume. In surface-limited systems, such as in trickling filters, the density of organisms is measured per unit area. Given an adequate depth of substrate, worms can be considered to be surface limited. So it is reasonable to express the density of worms in terms of their weight per unit area.

Loading rates at six different vermicomposting operations were evaluated to determine what S:W ratios have been used: consistently, daily feeding ratios in the range of 0.12 to 0.27 were obtained (Table 2-3). The relatively narrow range of values obtained is remarkable, because the criteria used in deciding on loading rates at most of the facilities cited here were based more on observation and previous experience than on rigorous computation of optimum loadings. More study is required to determine whether this range defines "optimum" worm feeding rates under constant conditions. If confirmed or modified experimentally, the S:W ratio could serve as a principal criterion in design of future sludge-vermicomposting facilities, as it is tied directly to process requirements.

Table 2-3

S:W RATES AT SIX VERMICOMPOSTING OPERATIONS

Location and Reference	Loading (wet weight)	Percent Solids	Worms (wet weight)	Days to Conversion	S:W Ratio
Akron, OH (6)	800 lb	15-20	400 lb	2	0.15-0.20
Keysville, MD (site visit)	300 lb	18	100 lb	2	0.27
Lufkin, TX (site visit)	2,500 lb	4	800 lb	1	0.125
Eugene, OR (4)	2200 lb	16	300 lb	10	0.12
Syracuse, NY (25)	30 parts by weight	11	1 part by weight	14 +	≤0.24
Syracuse, NY (25)	4 g	20	1 g	4	0.2

Note that the S:W ratio depends heavily on definition of "total conversion", the point at which conversion of sludge to castings is complete. There exists, at present, no standard definition of when the vermicomposting process is complete; operators often make judgments based on visual inspection of the wormbeds. (Note, too, that there is no need to consider worm weights on a dry basis: worms retain a relatively constant proportion of moisture -- approximately 80 to 85 percent of body weight -- under controlled conditions of vermiculture or vermicomposting.)

A more theoretical estimate would take into account only the volatile fraction of the sludge, but data are not yet available to extend the analysis.

Data on areal densities of worms are presented by Minnich (11). Worm densities reported for several small-scale vermicultural operations range from about 0.17 to 0.50 lb/sq ft, with an average of about 0.35 lbs/sq ft. At only two of the sludge-vermicomposting operations investigated in this study were areal densities reported. The estimated worm density at Lufkin's vermicomposting operation -- 0.42 lb/sq ft -- is close to the average density reported for vermiculture.

The density of worms used in vermicomposting dewatered sludge at Keysville, Maryland is much greater, at 1.33 lbs/sq ft. (Even higher densities have reportedly been attempted in this operation, but slime exuded by the worms was found to make the sludge bedding and castings difficult to handle and process.) If the areal density used at Keysville can be confirmed at other operations, it would suggest that densities of about three times those conventionally used in vermiculture might be appropriate for vermicomposting of sludge.

As noted above, the product of the sludge-to-worm ratio and the areal density provides a loading rate in terms of weight of sludge per unit time per unit area. At Lufkin, this product is approximately 0.05 lbs of dry solids per day per square foot. At Keysville, the ratio is about 0.36 lbs/d/sq ft. Because of the wide ranges found in practice in both the S:W ratios and the areal densities of worms, we suggest that research be conducted to better define the S:W ratio and the optimum worm density in order to obtain suitable design criteria defining the rate of sludge application per unit area.

Physical Effects

The most comprehensive analyses run on sludge and castings to date have been performed by Hartenstein et al, and most of the discussion that follows is derived from a paper completed by these researchers in 1979 (25).

The eating and defecating of sludge by worms significantly changes the physical and chemical properties of the sludge. The single most important change is the physical reduction of the sludge from an amorphous mass to the small cloddy particles called castings. Carmody has estimated that vermicomposting of a processed (shredded) solid waste will reduce particle size by 40 to 60 percent (1), which would signify a two-fold increase in surface area. For sludge, the reduction in size and concomitant increase in surface area are many times higher.

Three important effects of the increase in surface area might reasonably be expected: (1) the castings should dry more rapidly than sludge that has not been exposed to worm action, (2) the great increase in surface area should accelerate microbial activity over that in the sludge, and (3) the material should remain aerobic and relatively odor-free. Results of experiments have confirmed that all three expected effects do occur.

Drying. Side-by-side comparison of castings and the sludge from which the castings were derived shows that castings dry 1.5 to 2.1 times faster than the sludge (25). Spread in a layer 2.5 cm thick and kept at 105°C, castings were essentially dry 12 days after they were produced; sludge kept under the same conditions took 21 days to reach the same state. Because castings dry more rapidly than sludge, sludge mass is reduced much more quickly when sludge is exposed to earthworm action under proper conditions.

It has been observed that worms secrete around the castings a membrane that might serve to protect the worms from their feces (castings are generally toxic to the species of worm that produces them). A side effect of this process, however, might be that castings are kept separated from each other, thereby increasing the exposure of surface to air.

Microbial Activity. One measure of microbial activity in sludge is the rate at which oxygen is consumed by the sludge. Aerobically-digested sludge, dried to 20 percent solids and then maintained at 25°C, will reach a low steady state of oxygen consumption after about eight days.

The same sludge, when exposed to earthworm activity at 25°C, does not reach the steady-state level any more quickly, but it does show markedly higher oxygen-consumption rates during days 2 to 8. Hartenstein *et al* have calculated that the increased microbial activity supported on castings, as indicated by the elevated oxygen-consumption rates, means that an additional 19 percent of the sludge is oxidized as a result of the worms' eating (25). Actually, this bacterial increase could reasonably be attributed either to improved substrate conditions (increased surface area) or to a possible "bloom" of decomposer bacteria prompted by favorable growth conditions in the earthworm's gut. Whatever the cause, the effect -- significantly improved growth of microorganisms on earthworm castings -- has been observed in nature as well as in vermicomposting (10).

Aerobic Conditions. Because the castings remain aerobic, the odor-producing compounds -- such as amines, sulfides and phenolic compounds normally associated with anaerobic sludges -- are either oxidized or condensed (25). The castings have no offensive odor.

Chemical Changes

The earthworms' feeding on sludge changes its chemical composition in a number of different ways. Some of the changes are directly attributable to the worms' metabolism of the sludge: for example, some 0.5 percent of the nitrogen in sludge is assimilated by the worms for growth and cocoon production (25). Other chemical changes -- including a much more substantial reduction in nitrogen -- are due to microbial activity after the castings leave the worm; the activity is accelerated over what might occur in the absence of worms.

Hartenstein et al have conducted a series of experiments yielding the following summary of chemical changes in sludge subjected to worm activity (25). In their experiments, they used aerobically digested sludge centrifuged to 11 percent solids and maintained the sludge samples, with and without worms, at 25°C.

pH. The pH of sludge was depressed by E. foetida from levels of 7.0 to 7.1 to levels in the castings of 6.4 to 6.5. (Researchers working in field tests have recorded the opposite effect, such that addition of worms to mildly acid soils will gradually cause an elevation in pH (10, 11).)

Ash Content, Nitrogen, C:N Ratio. Side-by-side comparisons of sludge and castings over a four-week period yielded the following additional information, as summarized in Table 2-4.

Table 2-4

MINERALIZATION, REDUCTION OF NITROGEN, AND EFFECTS ON C:N RATIO IN SLUDGE WITH AND WITHOUT WORMS*

	Original Sludge	Sludge without Worms after Four Weeks	Sludge with Worms after Four Weeks
Ash content	29.3 ± 0.06	36.0% ± 0.04	38.4% ± 0.10
Carbon	39	36%	34%
Nitrogen	5.78 ± 0.02	5.08% ± 0.22	4.56% ± 0.03
C:N	6.74	7.08	7.46

* From (25)

The feeding activity of E. foetida accelerates the rates of mineralization and reduction of nitrogen. The fact that proportionally more nitrogen than carbon is lost due to earthworm action results in a higher C:N ratio in castings: 7.46 with earthworms present after four weeks versus 7.08 without earthworms and 6.74 in the original sludge. The decreases in nitrogen content are due in some small part to uptake of nitrogen by the worms, as mentioned earlier in this section, and probably in large part to activity of denitrifying bacteria and loss of ammonia to the atmosphere. Discussions of N-P-K concentrations and suitability of castings for agricultural use are contained in Section 4.

Heavy Metals and Other Elements. The aging of sludge causes a proportionate increase of heavy metals and other refractory materials, due to decreasing sludge mass from mineralization. As noted in Section 5, it is not clear whether the worms' activity changes the availability of these materials to the plants.

Section 3. PHYSICAL FACILITIES REQUIRED FOR VERMICOMPOSTING

Basis of Design

Because the approaches to vermicomposting used to date vary so widely from one installation to another, description of "an optimum process" or "typical facilities" is not possible. Sludge feed, application rates, methods of separating worms from castings, and wormbed configuration are among components of the vermicomposting process that are still in experimental stages. Nonetheless, based on what is known about vermiculture, sludge management, and the performance of worms in vermicomposting, facilities must be provided for the following functions:

- Wormbeds -- Since these worms are surface dwellers, and since it is crucial to maintain aerobic conditions and moderate temperatures in the substrate, the vermicomposting beds or windrows must be shallow.

- Sludge conveyance -- Depending on the nature of the sludge feed, sludge can be moved and distributed by manual, mechanical or hydraulic means.

- Shelter -- Structural facilities must protect against extremes of cold, heat, drought and moisture, all of which can cause loss of activity, migration, or death.

- Bed harvesting -- Collection of worms and castings can be accomplished by manual or mechanical means or by use of mobile equipment, such as a front-end loader.

- Separation of products -- Cylindrical rotating screens are commonly used for mechanical separation of worms and castings. Some other techniques require no special facilities or equipment.

In order to describe more specifically the types of equipment and facilities required for vermicomposting and to estimate their associated costs, we have developed as cases for study two installations that are based directly on facilities operating in Lufkin, Texas and Keysville, Maryland. The Lufkin facility accepts for vermicomposting a raw liquid sludge pumped directly from the city's wastewater-treatment plant, while the Keysville facility uses an aerobically-digested and dewatered sludge.

Reasonable design parameters are the sludge:worm ratio and the areal worm density (see Chapter 2). As shown in Table 2-3, the weight ratio of sludge (dry) to earthworms (wet) varies somewhat from site to site, but it averages about 0.20 lb/day/lb. And a worm density of about 0.4 lb/sq ft is common in vermiculture, although the Keysville operator reportedly uses more than three times that rate. The S:W of 0.2 lb/day/lb and the worm density of 0.4 lb/sq ft yield a loading rate of 0.08 lb/day/sq ft.

Liquid Sludge

Process Operation

For a facility processing liquid sludge, the sludge must be applied to an appropriate substrate material in order to maintain aerobic conditions in the bed. At Lufkin, this is accomplished by placing a 6- to 8-in. layer of sawdust as a bedding base and spraying sludge onto the sawdust using an in-place distribution system. To provide 0.08 lb/day/sq ft, about 0.24 gallons of 4-percent-solids sludge would be dosed per square foot of bed area. This dosage would be applied on a daily basis. At two-month intervals, a 1- to 2-in. layer of sawdust would be added to the beds. The operator at Lufkin believes this is required because there is some consumption of the sawdust by the earthworms (Ed Green, personal communication). Eventually, the castings would build up on the bottom of the bed, since they are a denser material than the sawdust.

The castings/earthworms mixture would be removed (harvested) from the beds every 6 to 12 months and fresh beds constructed. Although material had not been removed from the Lufkin beds at the time of this writing, the operator reported that he plans to use a migration technique. (Mechanical screening technique is discussed below for the dewatered-sludge case.) The migration technique would be accomplished in two steps. In the first step, a small front-end loader, tractor or other vehicle with a blade attached would drive onto the bed and windrow the vermicomposted material. Next, a food source such as sludge would be spread adjacent to the windrow(s). After a day or two, nearly all the earthworms would be expected to have migrated to the new material. The windrows, which now would consist primarily of castings and substrate, would then be removed, leaving a high-density pile of earthworms in the adjacent temporary bed. The earthworm would then be used to stock a new bed, and the cycle would be started again.

Equipment Requirements

The equipment required for liquid-sludge vermicomposting includes that needed for sludge distribution and for harvesting. At Lufkin, sludge is pumped via a force main from the wastewater-treatment facility over a distance of several hundred feet to the vermicomposting beds. The force main connects to a lateral along each long side of the 20-ft x 95-ft beds (see Figure 3-1). Spring-loaded valves placed at intervals of every 25 to 30 feet distribute the sludge over the bed area.

Alternative methods of bed configuration and distribution are possible. The pumping and distribution system should be designed to minimize the amount of sludge remaining in the pipe after the daily dosing. This condition results in septicity and has caused some problems at Lufkin. Should small-diameter piping be used, it might be necessary to install a grinder or mazerator ahead of the piping, depending on the nature of the sludge used. Pumping and distribution system controls should be located within view of the beds so that the operator can monitor the dosing operation.

FIGURE 3-1
REPRO SIZE 6 x 3 3/4
R 80%

Figure 3-1 Sludge force main and laterals for distributing raw primary and waste activated sludges to worm beds, Lufkin, Texas

Mobile equipment requirements consist of a small front-end loader for initial bed construction and harvesting. The operator at Lufkin has suggested that a more specialized machine could be used to remove material from the bed, such as a "poultry-house cleaner" used commercially in the poultry-raising industry to remove bedding and poultry manure for later agricultural use.

Building Requirements

Building requirements are based on the rate of sludge conversion per unit of area. As was discussed above, a loading rate of 0.08 lbs of dry sludge per day per square foot is reasonable. For a one-dry-ton-per-day facility, approximately 25,000 square feet of bed area would be required. Based on area requirements for pumping and walkways of an additional 15 percent, a 29,000-sq-ft building would be required. (If worm density could be tripled, as is done at Keysville, the total area needed would drop to about 10,000 sq ft).

At some vermicomposting facilities, the building requirement is met by using an unused portion of a covered sludge-drying bed or by leasing an unused barn or similar structure. For this report, we have considered two types of structures. The first is a prefabricated "greenhouse-type" building that might be utilized in northern climates. The building is capable of withstanding snow loading and could be heated by solar heat or by conventional means. The second type of structure is like the one used at Lufkin and is appropriate for warmer climates (Figure 3-2). It consists of a simple arched steel frame with two layers of 6 mm polyethylene cover material. The outer layer of polyethylene is dark, the inner layer is transparent. The outer layer can be removed during the winter months to allow the sun to heat the beds though the inner layer. Alternatively, with both layers in place and the ends of the structure open, the beds can be kept at reasonable temperature levels during the summer months. The life of the polyethylene cover might be only about two years, depending on method of handling and climatic conditions.

FIGURE 3-2
REPRO SIZE 6x4
R 65%

Figure 3-2 End-on view of simple vermicomposting structures suitable for use in warmer climates, Lufkin, Texas

Dewatered Sludge

Process Operation

For a facility using dewatered sludge, the operation might be similar to the existing pilot-scale operation in Keysville, Maryland. This facility is processing only about 54 lb of dry solids per day.

At Keysville, vermicomposting takes place on two 75-sq-ft beds. Dewatered sludge, concentrated and air-dried to about 18-percent solids, is shoveled onto the beds from a wheelbarrow. The sludge is leveled to a uniform depth of about two inches, and the earthworms are then weighed and distributed evenly atop the beds. Over a two-day period, the earthworms convert the sludge into castings. At the end of this period, the castings-earthworm mixture is removed from the beds. The earthworm-castings mixture is fed the slightly elevated "feed" end of a cylindrical rotating screen. As the material is tumbled by gravity down the length of the screen, the castings fall through the screen and the earthworms pass through to the discharge end where they are collected. The earthworms are then available for reuse. Labor requirements total approximately two hours per day to load, unload, and screen materials.

The wheelbarrow-shovel operation used at Keysville would be inappropriate for a larger facility (a 1-ton-per-day facility would, after all, process about 40 times more sludge than is currently being processed at Keysville). A large operation would require mechanization. Dewatered sludge cake would be transported to the bed by conveyor and leveled using an automatic device. After two days, the bed would be unloaded automatically. This might be accomplished by designing each bed as a movable belt conveyor. In this way, the material could be discharged directly to another conveyor which would transport material to the screening device.

The operator at Keysville reports that about one percent of the earthworms are lost in the harvesting process per week. Due to the low residence time in the beds and the intermittent disturbance caused by harvesting, earthworms in the vermicomposting beds might have little or no opportunity to breed and maintain the population level. In addition, many of the juvenile worms that do hatch in the beds fall through the harvesting screen with castings. Therefore, in order to make up for worm loss, new stock must be purchased regularly or several undisturbed beds must be set aside strictly for breeding activity.

Equipment Requirements

The major items required for vermicomposting of dewatered sludge are the beds and material-transfer and harvesting equipment. The beds used at Keysville are constructed of wood and wire screens. The sides of the bed are approximately 4 inches high, which provides for a 2-inch freeboard above the surface of the mixture. The freeboard is required to keep material from dropping to the floor during bed loading and unloading. The bottom of the bed consists of a fine wire-mesh screen (the operator recommends an eighth-inch screen, but is currently using common window screening). Screening, rather than wood, is used for the bed bottom, in order to promote aerobic conditions throughout the 2-inch layer of material.

The operator at Keysville has suggested that the beds could be stacked to save space. Such a stacking arrangement is very common in the earthworm-breeding industry.

A harvesting device used at several installations consists of a cyclindrical screen from 8 to 12 feet long and of about 2 feet in diameter (see Figure 3-3). The screen is rotated by a small-horsepower motor via a belt or by direct drive along a central shaft. The screen is usually divided into two or three sections of different mesh sizes in order to screen products of varying sizes.

FIGURE 3-3
REPRO SIZE 6x5
R807

Figure 3-3 Typical rotating harvesting device for separating earthworms and castings

Building Requirements

A building for handling sludge cake would be more compact than one for liquid sludge, because the worm beds would likely be stacked. Three-tiered operation would cut area to about one-half the requirement for liquid sludge - about 15,000 sq ft per ton/day of sludge for a worm density of 0.4 lb/sq ft and about 5,000 sq ft per ton/day of sludge for a worm density of 1.2 lb/sq ft.

As was suggested earlier, vermicomposting beds can easily be constructed within an existing building. The two types of structures described earlier for different climatic conditions would probably be generally acceptable for vermicomposting of dewatered sludge.

Section 4. VERMICOMPOSTING PRODUCTS AND PRODUCT MARKETING

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 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. 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. It is not known what other states, if any, have promulgated regulation of vermiculture or have authorized its support.

Worm Castings as a Product

The worms' castings must be periodically removed from the vermicomposting beds, as the castings apparently contain substances that are toxic to the earthworms (12). The methods used to separate earthworms from castings are discussed in Chapter 2.

The 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 sludge (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 sludge through the earthworm's gut significantly alters the physical structure of the sludge. Large sludge particles are broken down into numerous smaller particles, with a resultant enormous increase in surface area (17). As a result of the increase in surface area (as discussed in Section 2), the castings dry about twice as fast as the original sludge, remaining odor-producing sulfides are completely oxidized, microbial respiration is accelerated by a factor of 3, and _Salmonella_ bacteria are destroyed about twice as rapidly as in the original sludge (7, 25).

The chemical composition of castings derived from sludge reflects that of the original sludge. Increases will be observed in the concentrations of some constituents (such as sodium, calcium and heavy metals), and decreases in others (such as carbon and nitrogen) as described in Section 2, Performance in Vermicomposting.

Remarkable claims have been made for other 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 surface-casting species such as _Lumbricus terrestris_ and _Allolobophora longa_ than to those produced by vermicomposting worms. In fact, the percentage of humic acid in castings produced by _E. foetida_ has been shown to decrease to below the percentage for control sludge (sludge without worms), over a 28-day period, despite an initial increase in the first five days (17).

Agricultural Value

Table 4-1 shows nitrogen-phosphorus-potassium (N-P-K) concentrations in aged, aerobically-digested sludge from a wastewater-treatment plant in New York State. These values would give an N-P-K ratio for the sludge of 5-3.5-0.5. _E. foetida_ fed on this sludge produce castings with a virtually identical N-P-K ratio of 4.5-4-0.5. For purposes of comparison, heat-dried sludges produced as soil supplements in Houston, Chicago and Milwaukee have N-P-K ratios of 5-4-0, 5-4-0.5, and 6-2-0, respectively. Raw sludges subjected to thermophilic composting have N-P-K ratios on the order of 1-1-0.2 (28).

Table 4-1

N-P-K RATIO IN SLUDGE AND CASTINGS*

	Sludge (original values)	Sludge (after four weeks)	Castings
	%	%	%
N	5.78	5.08	4.56
P as P_2O_5	3.30	3.78	4.05
K as K_2O	0.48	0.51	0.57

*From (25)

The nitrogen in castings is not all available immediately for plant uptake (29); this means that castings could 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 sludge feed. Castings derived from an aged anaerobic 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 (30). Analysis of castings derived from a wide variety of feeds (not necessarily sludge) showed most contained amounts of sodium or other salts that would be detrimental to plant growth (29).

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 (31).

Anticipated Market Development

The existing or potential markets for castings include:

- Use as an ingredient in potting mixtures
- Sale or distribution as an organic soil amendment
- 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. 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. One vermicomposting operation is currently producing and marketing a castings potting mix that is sludge derived, but regulations in other states might preclude sale of such a product.

Competition in this market can be expected from conventional potting mixes, which are often less expensive, and from vermiculturists selling high-grade mixtures derived from worms feeding on a variety of non-sludge substrates.

The second market -- bulk sale or distribution of casting as an agricultural soils' amendment -- is more compatible with the scope and purpose of sludge-processing operations. Competition here would be represented by other sludge "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 per dry ton.)

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 sludges that are proposed for land application. Passage of sludge through the earthworm's gut and its subsequent mineralization increase the concentrations of heavy metals that are present in the sludge. Some of these metals can be injurious to plant growth, and some can be accumulated by organisms in the food chain to levels that might be harmful to humans. This constraint is discussed further in Chapter 5.

In summary, some nutrients of agricultural benefit are present in castings produced by worms feeding on sludge. Castings could, therefore, be a valuable soil amendment, provided that the original sludge contained normal proportions of plant nutrients and was not heavily contaminated by potentially toxic substances. In rural and suburban areas, there might be sufficient demand for this product to realize some income from sale of the castings to farmers and property owners. In other areas, the product might be used in bulk by municipal parks and grounds departments or public works departments. It could also serve as a nutritive substrate mixed with soils for reclamation of disturbed lands.

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" (32). Entrepreneurs in the vermiculture industry have made claims for a virtually unlimited market serving the following sectors:

- Sport fishing (32)
- Inoculation of horticultural (16) or agricultural soils or reclaimed lands (8, 11)
- Fertilizer or soil supplement (33)
- Animal feed (34)
- Worm stock for vermiculturists (8, 11)
- Human nutrition (16, 35)

Of these market sectors, the only "large stable market" for vermiculturists, at present, involves sale of baitworms (36). 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 (11, 37), 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 (11), $50 million (37, 38), and $80 million (8). 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 (8).

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 (36).

Beyond the constraint posed by lack of market capacity, distribution of live earthworms that have been raised in sludge could pose public health hazards through exposure of buyers to pathogens contained in or on the worms' bodies or in the substrate. The difficulty of separating live earthworms from disease-producing microorganisms would appear to eliminate the bait market from serious consideration for a sludge-vermicomposting operation, despite the central importance of this market to the vermiculture industry. 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 sludge-raised worms in the baitworm market.

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" (36). 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 (8).

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 (11); their activity during this season is unlikely to improve soil humification or water-holding characteristics. 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 sludge. The worms could not be supported in the soil without additional applications of sludge at periodic intervals (11). 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 city refuse annually would yield a byproduct of dehydrated earthworms totalling 150,000 tons of 10-percent nitrogen material (33). 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 $2.50 per 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. Loss of one percent of the worm population per week -- as is estimated at the intensively cultured indoor vermicomposting operation at Keysville, Maryland -- requires substantial makeup. Excess worm stock at such a facility must be maintained in breeder beds both for routine make-up and as backup in case of system failure.

Even if use of worms as fertilizer could be justified on economic grounds, environmental constraints would operate on this market. Unpublished results obtained by Neuhauser show that concentrations of nickel, copper, zinc, lead, chromium and cadmium all increase in worm bodies within four weeks of first exposure to sludge. A side-by-side analysis performed on castings and worms from a vermicomposting operation in San Jose shows cadmium at 32 mg/kg in castings and at 43 mg/kg in the worms. Elevation of cadmium or other heavy-metals levels in any soils-amendment product could jeopardize its acceptability.

Worm Stock for Vermiculturists

Vermiculturists consider this market to be second only to the fishbait market in its potential (8, 11). Assuredly, it is a market that has served some entrepreneurs well indeed. Some practices in this market, however, have been legally questionable and have cast a shadow on the larger industry. "Binning" and "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 the shutting down of worm-distribution operations in several states (including Florida, Oregon, Wisconsin, Colorado, and California). Buy-back agreements with fixed price guarantees are subject to regulation by the U.S. Securities and Exchange Commission (8).

This is not a viable market for the composting operation, due in part to the potential transmission of disease by pathogenic bacteria and viruses attached to worms that are raised in sludge. Some have speculated that sale of cocoons, rather than live worms, might be feasible (39, 40). 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.

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 (8) 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
- 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. A typical advertisement in an industry journal (The Vermiculture Journal, Vol. 2, No. 1, January 1979) reads:

> "Lively fat redworms. Satisfaction
> guaranteed. Dealers are welcome.
> 1,000 - $5.50; 5,000 - $25.00.
> Free information..."

No reliable analysis has been made of market potential; there is every likelihood that entry of a few major new cocoon or worm suppliers would swamp the market and drastically reduce prices.

Animal Feed

The composition of *E. foetida* is high in protein, as shown in Table 4-2. A comparative analysis of amino-acid composition in worm meal and commercial-grade meat meal and fish meal, as shown in Table 4-3, indicates that "the earthworm product has a relatively high level of the essential amino acids, particularly the important sulphur-containing ones (cysteine and methionine)" (35).

Worm meal can be prepared by washing worms clean and then freeze-drying or low-temperature hot-air drying the worms (35). Two University of Georgia researchers have found that dried earthworm meal was palatable to domestic cats (19). 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 (35).

Table 4-2
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 (35)

Table 4-3
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 (35)

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

Those in the vermiculture industry who have investigated this market (4) report that, in order to be competitive, worm meal must be priced in or near the range of $0.10 per pound (1979 prices for meat and bone meal) to $0.17 per pound (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 (36), 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 (although at least one waste-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 (8).

The same market constraints as are reported for other uses of live worms apply to the feed market. The presence of pathogens in the sludge substrate and attached to 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 -- all make it essential that distribution, sale and use of sludge-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 sludge could prevent excessive accumulation of heavy metals in worm tissues.

Human Nutrition

The public-health constraints that apply to any of the market sectors for earthworms apply the more forcefully to use of sludge-raised worms for human nutrition. This is not a viable market for the composting operation.

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 sludge-derived product. The nutrient value of castings, however, and their aesthetic and handling characteristics make them a desirable agricultural soils amendment. Provided that the sludge from which the castings are derived is relatively "clean", in terms of heavy metals and toxic synthetic organics, 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.

While prospects are dim for product income offsetting production costs, this market would serve, at the very least, to reduce or eliminate a municipality's current costs for final disposal of sludge.

Section 5. ENVIRONMENTAL AND PUBLIC HEALTH ASPECTS OF VERMICOMPOSTING

The potential benefits and risks associated with use of a sludge-vermicomposting product include the following:

- Beneficial addition of nutrients and organic material to soil
- Risk of heavy-metals' buildup in soil and subsequent uptake by plants
- Potential for pollution of ground and surface water by nitrates in sludge
- Restricted land use at application site
- Potential dispersal of pathogens

Vermicomposting must address all of these areas of concern, as well as potential risks at the vermicomposting site.

Potential On-Site Problems

Odors

Most problems of sludge odor are aggravated or caused by anaerobic conditions in the sludge. As earthworms cannot long survive anaerobic conditions nor thrive in anaerobically digested sludge, successful vermicomposting will rely on maintenance of aerobic -- and, therefore, relatively odor-free -- conditions.

The use of vermicomposting techniques that hasten conversion of sludge into castings will virtually eliminate the 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 airtight 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 and that there were no indications of hydrogen sulfide or anaerobic conditions (41).

Odors were not found to be a problem at any of the pilot- or full-scale vermicomposting operations visited for this study.

Vermin

If not controlled, flies and other vermin can cause severe nuisance problems at any sludge-handling facility where sludge is left exposed. Conceivably, these vermin could act as vectors in transmitting pathogens. Several aspects of the vermicomposting process might alleviate the problem, however. First, it appears that sludge can be vermicomposted quite rapidly, under certain conditions, thereby reducing the amount of time that raw or freshly digested sludge is exposed at the site. Second, the fact that turnover is so high -- and that worms are actively burrowing in the sludge throughout this period -- means there should be little or no opportunity for fly larvae to hatch and thrive in the sludge (1). And third, as the conditions of vermicomposting require that structural facilities be erected to protect the operation from climatic extremes in most areas of the United States, it should be relatively simple to screen the facilities to reduce numbers of flies and other animals at the vermicomposting facility.

Some flies were observed at the Lufkin, Texas vermicomposting facility. According to he operator, the flies at the vermicomposting site were no more populous than he had observed at the nearby water-pollution control plant. Flies posed no nuisance problems at any other vermicomposting facility visited.

Enclosure of the facility or installation of protective screens would also prevent predation by ground squirrels, moles, armadillos and birds, all of which have been known to eat worms. Collier notes that small animals have caused no severe problems at his windrow operation, despite the fact that it is located near a sanctuary for birds and other animals (42).

Site Runoff and Leachate

Where facilities are enclosed, runoff and leachate will not be problems. In fact, the optimum moisture content for sludge that is to be vermicomposted is low enough that even its placement in screen-bottomed beds (as is done at Keysville, Maryland) results in no dripping or pooling of moisture that would have to be controlled. The use of unprotected beds or windrows for vermicomposting, however, would necessitate site-design and process-operation features to control potential pollution of groundwater and surface water by high biochemical and chemical oxygen demands, suspended and dissolved solids (including chlorides and nitrates), pathogenic bacteria, color, iron and other metallic ions, and low pH.

If control of surface runoff is necessary, it should be collected for discharge to sewers, or be stored in holding tanks for later disposal to sewers or for separate treatment by irrigation or other means.

Leachate at an open or semi-enclosed vermicomposting facility 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. This will prevent the flow of polluting nutrients or toxic materials into groundwater supplies.

Workers' Safety

Potential risks to workers' safety and health appear to be fewer at a vermicomposting facility than at a conventional wastewater-treatment plant. Some operational activities, however, could pose problems. Spraying liquid sludge onto the wormbeds might generate aerosols carrying fungal spores, pathogenic bacteria, or viruses. The hazard would be more severe is spraying were done within the confines of an unventilated structure. Another possible health problem could be caused by the dusty conditions sometimes created when mechanical screening devices are used to separate earthworms from castings. Routine safety and hygienic practices, including masking of operators during critical operations, will help to protect workers' health.

Access to a vermicomposting facility should be controlled in order to avoid unnecessary exposure of the general public to the pathogens that can be present in sludge and castings. Some existing pilot-scale facilities are basically backyard or barnyard operations that are easily accessible to children. The fact that vermicomposting might be an "appropriate technology" in some rural and suburban areas should not be permitted to encourage a casual approach to the handling and management of wastewater-derived sludges.

Potential Risks in Dispersal of Products

As discussed in Section IV, the vermicomposting operation yields two products -- castings and worms -- for which there are potential markets. Some of these potential markets are constrained by real limits on demand, and others, by environmental problems that might result from increased dispersal and application of sludge-derived products. Of primary concern among these potential environmental problems are the toxic substances and pathogenic microorganisms that are present in raw sludge.

Toxic Substances

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 sludge, however, there exists a potential for contamination of the product by heavy metals, chlorinated hydrocarbons and other toxic substances. Considerable research has been done in this area, and the best information to date indicates that vermicomposting does nothing to solve the problem of toxic constituents in sludge. Castings will contain concentrations of heavy metals as high as or higher than the sludge from which the castings were derived.

Sludges that are relatively free of heavy metals and toxic organics will be suitable for vermicomposting and subsequent use in agricultural applications; "borderline" sludges and those that are high in concentrations of toxic substances will not be acceptable.

Heavy Metals. Constituents of concern include the heavy metals cadmium, copper, nickel, zinc, lead, and chromium, all of which can have toxic effects on plants (25). High levels of copper will kill earthworms. Cadmium in soils can accumulate in plants to levels believed to be harmful to humans.

Hartenstein et al have shown that aging of sludge over four weeks' time will significantly increase the concentrations of all of these heavy metals, due primarily to the mineralization and loss of organic mass that occur as sludge ages. Because vermicomposting promotes these aging effects, concentrations of heavy metals increase even more. Unfortunately, mass balances have not been done yet, so the exact fate of the metals is not known.

It is not clear whether worm activity changes the availability of metals to plants. According to research reported in Edwards and Lofty (10), the 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 (9).

Some of these metals are also accumulated in worm tissue, which could be of concern if the worms were to be disposed of haphazardly or otherwise dispersed into the environment. 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 (43, 44).

Most researchers have found that worms accumulate the following heavy metals: cadmium (9, 43, 44, 45, 46), copper (43, 37), nickel (44), mercury (48), zinc (43, 44, 45, 49, 50) and lead (44, 45, 49, 50). Whether this concentration actually occurs in worms feeding on sludge under conditions of vermicomposting is another question. 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.

Over short residence times of a month to a month-and-a-half, worms (Aporrectodea tuberculata) have been shown to accumulate readily cadmium, copper, mercury, silver and zinc, if those metals are supplied to the worms in soluble form (43). These metals might not all be soluble or biologically available to earthworms, however, in sludges obtained directly from a wastewater-treatment plant. A four-week laboratory study of E. foetida feeding on dewatered waste activated sludge showed no significant accumulation of cadmium, chromium or nickel, but did show accumulation of copper, zinc and lead (47). Mercury as present in sludge was not taken up by worms, and chromium was not taken up in any form (43).

Effects of aging and microbial action in sludge might gradually release the heavy metals in sludge in forms available for uptake by worms. Helmke recorded cadmium levels of up to 118 ppm in worms collected from a former 60-ton-per-hectare sludge application plot (43); the sludge itself contained 102 ppm of cadmium. Ireland found that worms grown in heavily contaminated soils contained proportions of soluble zinc and lead (and calcium) that were significantly higher than those in the worms' castings or in the soil itself (50).

Other Toxic Substances. 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:

DDT and residues	9.0x to 10.6x soil levels
Aldrin	3.3x soil levels
Endrin	3.6x soil levels
Heptachlor	3.0x soil levels
Chlordane	4.0x 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 (10).

Organophosphorus insecticides such as parathion do not appear to be concentrated by worms (10).

When toxic substances in sludge limit its suitability for use as a soils' amendment, it will usually be the heavy-metals' component that is in violation of EPA guidelines. Nevertheless, as discussed above, worms used in vermicomposting are known to concentrate other toxic, persistent substances in their tissues. More research is needed in this area of the environmental aspects of vermicomposting.

Pathogens

Because pathogenic microorganisms in sludge are known to live up to six months after sludge is applied to land (51), the presence of these pathogens could limit the market acceptability of sludge-derived castings proposed for use as a soils amendment. Certain features of the vermicomposting operation might lessen this constraint, however. For example:

- Salmonella bacteria present in sludge are destroyed about twice as fast in the presence of E. foetida as in the worms' absence (7)

- Evaporation of moisture in sludge dramatically increases the inactivation of viruses present in the sludge (52); since castings dry about twice as fast than the sludge from which they are produced, vermicomposting could accelerate inactivation of viruses.

The Texas Department of Health found no Salmonella in sludge-derived castings or in live earthworms used in a Shelbyville vermicomposting operation. At the time, the Shelbyville facility was vermicomposting raw sludge obtained from the Center, Texas wastewater-treatment facility (41).

There are various methods to sterilize or reduce the number of pathogens in sludge. Research conducted at Sandia Laboratories in Albuquerque, New Mexico has shown that survival of viruses is reduced by four orders of magnitude as sludge is air-dried at 21°C from 5-percent solids to 83-percent solids (52). Castings spread in a 2.5-cm layer at 25°C will be dried to 83-percent solids within 10 days of egestion (25), and this drying process should kill or inactivate most pathogens present in the sludge (unless some unknown characteristic of the castings "harbors" pathogens and protects them from inactivation).

Castings might be sterilized by steam treatment, open-flame heating, or exposure to 100-percent methyl bromide gas for a 24-hour period (J. McClarran, personal communication), but the efficacy of any of these methods is not known.

It is not clear how the current EPA criteria for landspreading of sludge would be applied to a vermicomposting product. Criteria published on 13 September 1979 link degree of sludge treatment to proposed agricultural use.

Under some circumstances, according to the EPA criteria, sludge need only be treated by one of the specified "Processes to Significantly Reduce Pathogens". These processes -- aerobic and anaerobic digestion, air drying, low-temperature composting, lime stabilization, and "equivalent methods" -- are considered adequate for treatment of sludges that are to be applied to non-agricultural land or agricultural land where the edible portion of the crop will not come into contact with the sludge. "Processes to Further Reduce Pathogens" -- high-temperature composting, heat drying, heat treatment, thermophilic aerobic digestion, and equivalent processes -- are necessary for treatment of sludge applied to croplands for human food (although any of the "significant reduction" processes, if followed by pasteurization or irradiation, also suffices for this purpose). Application of any treated sludge to land must be accompanied by control of public access for at least 12 months and prevention of grazing by meat and dairy animals for at least one month after application.

Vermicomposting is a low-temperature process that does not itself reduce pathogen levels; apparently, however, it creates conditions that subsequently accelerate the reduction of pathogens to a significant degree. It might be necessary to establish specific conditions of vermicomposting, such as maintenance of a defined "curing" period for castings, before vermicomposting of raw sludge can be considered a "significant reduction" process.

Section 6. ECONOMICS OF VERMICOMPOSTING

Basis of Cost Estimates

We have used as a basis for developing cost estimates the structural and equipment requirements identified in Section 3. All costs are based on present-day prices. They might be optimistic, because vermicomposting is now in a developmental stage. The technique is being tested and demonstrated in order to establish technical feasibility and not to define associated costs. Costs have not been closely documented by operators at any of the facilities researched or visited in the course of this investigation.

In this section, costs are estimated for vermicomposting one dry ton per day of sludge -- an amount of sludge that could be expected from a one-million-gallon-per-day (1-mgd) facility treating domestic wastewaters. A treatment plant of this size normally would serve a municipality of 10,000 to 15,000 persons. The costs developed are based on a sludge loading rate of 0.08 lb/day/sq ft (sludge:worm ratio of 0.20 lb/d/lb and a worm density of 0.4 lb/sq ft).

Costs of Vermicomposting Liquid Sludge

Initial capital costs and total annual costs for vermicomposting a liquid sludge are presented in Table 6-1. Included among the capital costs are land and site development costs, a building, and initial earthworm stock and equipment.

Capital Costs

Land and Site Development. As was shown in Section 3, the total building area required for this vermicomposting facility would be about 29,000 square feet. The actual area of land to be purchased would depend on its proximity to the wastewater-treatment plant, site topography, and other factors. A vermicomposting facility located at the treatment plant and, therefore, having only minimal buffer requirements would require about 1 acre of land in order to allow for access roads and other ancillary facilities.

In this estimate, costs are based on $5,000 per acre for land and an additional $15,000 per acre for site development. These costs will vary considerably from site to site. Costs will be greater in urban areas or where extensive grading is required.

Building. Total costs might be reduced by leasing space in underutilized buildings. The experience at all vermicomposting operations except Lufkin has involved purchase or lease of abandoned sludge drying beds, barns and other structures. The principal consideration in converting and utilizing existing structures is what additional transportation costs might be incurred.

Costs for a building are based on the types of structures described in Section 3. The low end of the estimated range of costs in this category is based on the "Lufkin-type structure", which was constructed at an actual cost of approximately $2 per square foot. The second type of building described in Section 3, a prefabricated metal structure or greenhouse, was used as the basis for the upper end of the estimated range of costs. Such a structure might cost approximately $20 per square foot including equipment for heating and ventilation. Based on the estimate of 29,000 square feet, the building will cost from $58,000 to $580,000, depending on the type of structure used.

The cost of constructing a building represents the single largest cost in vermicomposting liquid sludge. Depending on the geographical location of the facility, the building represents 20 to 60 percent of the estimated annual cost of this process. Although it might be possible to operate a vermicomposting facility in windrows and beds constructed out-of-doors (as has been done on a small scale at Titusville, Florida and Ridgefield, Washington), the facility would probably be limited to seasonal operation, and conversion rates presented in this report would probably not be consistently maintained. The worms' performance is best if temperatures are kept to between 13°and 22°C, as discussed in Section 2.

Earthworm Stock. Earthworms (*Eisenia foetida* and/or *Lumbricus rubellus*) would be purchased in order to stock the vermicomposting beds. At a S:W ratio of 0.20 lb of sludge per lb of earthworms, approximately 10,000 lb of earthworms are required for a 1-TPD facility. The cost of earthworms at Lufkin, Texas has been reported at $1.20 to $3.75 per pound; for this report, we have used an average cost of $2.50 per pound. (A pound of earthworms represents a population of approximately 1,000 worms of mixed sizes.)

The cost of the initial stock of earthworms is $25,000. We have assumed that this stock would be purchased only once and that the worms' breeding in the vermicomposting beds would maintain or increase the population throughout the life of the facility. Earthworms might also be sold at the end of the project life at a cost equal to or exceeding the initial cost. For planning purposes, however, this income cannot be counted on. Some vermicomposting operators have suggested that only one third to one-half of the total stock required should be purchased initially, with the process to be phased into full operation over a period of several months as excess earthworms are produced. Research is needed to determine the rates at which earthworms will breed under conditions of vermicomposting.

Equipment. Equipment required for vermicomposting liquid sludge includes a sludge-pumping and -distribution system and a front-end loader or other device for transfer of materials. As the harvesting of castings (or castings and earthworms) occurs only periodically, existing municipal equipment, if available, might fill this requirement. For this report, we have used a cost of $40,000.

Total Capital Costs. Total capital costs are $143,000 to $615,000, depending on the type of structure used. To express the costs in terms of equivalent annual costs, at a 7-percent interest rate, varying service lives were used. The Lufkin-type building and all equipment were amortized over 10 years. All other costs, including land and site development, the prefabricated building, earthworms, and equipment, were amortized over 20 years. The total equivalent annual costs ranged from $18,000 to $66,000.

Annual Costs

Annual costs include labor for operation, utilities, and maintenance, in addition to the amortized capital costs developed above.

Operation. Labor costs are low for this type of facility, because daily tasks consist of no more than applying sludge to the beds, routine tests and maintenance which should take no more than 2 hours per day. Every 6 to 12 months, the harvesting operation will require approximately 8 workhours per 2,000 square feet of bed area. For a 25,000-sq-ft bed handling 1 dry ton per day, a total of about 2-1/2 workweeks would be required annually for harvesting. Up to an equivalent amount of time might be required to construct new beds. Total labor would amount to one-third to one-half of an operator's time. Costs are based on an annual salary of $15,000, including fringe benefits. This cost will vary somewhat, depending on the region.

Utilities. Utility costs include power for pumping and lighting (if required) and fuel for heating and machine operation. Based on the estimates of the Lufkin facility, these costs should be about $2,500 to $3,000 per year. An annual cost of $5,000 was used in this report to account for heating costs that would be incurred in northern climates.

Maintenance. Costs are included for maintenance and materials, at approximately 5 percent of equipment costs.

Miscellaneous. Miscellaneous costs include allowance for sawdust and replacement parts. Based on yearly harvesting, about 8 inches of sawdust are required per year, or about 600 cubic yds per year for a 1-TPD facility. Approximately 400 additional cu yds per year might be required periodically to replenish the beds. Sawdust costs vary widely, depending on the local supply. At Lufkin, sawdust is obtained free of charge from a local mill, and the transportation cost to the municipality is low. Costs for sawdust in this report are based on $2.00/cu. yd.

The polyethylene covers used at Lufkin have a life of only about 2 years. The reported installed cost at Lufkin was approximately $0.25 per sq ft of bed area. Based on 29,000 sq ft of area and replacement every other year, annual costs for this type of facility would increase by about $3,500.

Total Annual Costs. Total annual costs for vermicomposting of liquid sludge are $38,000 to $86,000 per year including amortized capital costs. Actual costs would depend on the location of the facility and the type of structure built.

Comparison of Unit Costs

A unit cost for vermicomposting liquid sludge can be computed by dividing annual costs by the number of dry tons processed yearly (365 tons). Unit costs of about $105 to $235 per dry ton are computed for a loading of 0.08 lb/day/sq ft.

Two variables relating to worm density could affect the unit costs developed for vermicomposting. As was presented in Section 3, the S:W ratios encountered in this investigation ranged from approximately 0.12 to 0.27; 0.2 was used as a basis for estimates in this section. Worm densities per unit area of up to three times those used as a basis for cost estimates in this section have reportedly been successfully used in some vermicomposting operations. If feasible for full-scale practice, the use of higher sludge loading rates might halve the unit costs of vermicomposting.

These unit costs are quite reasonable when examined against those for other, more conventional processes for facilities of similar size. For example, trucking and land-spreading one dry ton per day of liquid sludge might be expected to cost about $70,000 per year or about $190 per dry ton. Other options might include dewatering and static-pile composting or dewatering and landfill. Costs for these systems might be expected to range between $175 and $250 per dry ton, depending on transportation costs.

These costs place vermicomposting of liquid sludge in a very competitive posture with other contemporary sludge-management practices.

Costs of Vermicomposting Dewatered Sludge

The process as presently practised at Keysville is too labor-intensive for any facility much larger than the present operation. At Keysville, about 300 lb of 18-percent-solids sludge (54 lb) are processed per day. Labor requirements total approximately two hours per day to load, unload and screen material from a 75-square-foot bed. At this rate, seven operators -- shoveling cake and castings full time -- would be required for a facility processing one dry ton per day. Depending on the loading rates, total annual costs would amount to about $360 per dry ton, with labor alone accounting for about $300 per ton. Not only is this cost high, but also the problem of hiring and motivating staff for so menial a task appears insurmountable. This method of operation clearly is limited to small facilities that would be required to use their labor force only part time for vermicomposting.

A municipality planning for vermicomposting of dewatered sludge would undoubtedly construct a highly mechanized system that would reduce the high labor requirements. At this point, however, no such system has been designed nor are there reliable estimates of its cost. If mechanization of this vermicomposting process could be developed at reasonable cost (thereby reducing labor requirements), the process might be competitive with conventional practices.

Table 6-1

COSTS OF VERMICOMPOSTING ONE DRY TON PER DAY OF LIQUID SLUDGE

Capital Costs	
Land and Site Development	$20,000
Building	58 - 580,000
Earthworms	25,000
Equipment	40,000
Subtotal	$143 - 665,000
Annual Costs	
Amortized Capital Costs	$18 - 66,000
Operation	7,500
Utilities	5,000
Maintenance	2,900
Miscellaneous	4,700
TOTAL	$38 - 86,100
UNIT COST ($ per dry ton processed)	$105 - 235

Section 7. FINDINGS AND RECOMMENDATIONS

Major Findings

1. Vermicomposting is in its infancy. Vermicomposting of municipal wastewater sludges has been considered seriously only within the last 10 years. Research and demonstration have been conducted only at small scale. No one technique of vermicomposting has been accepted as optimum; no full-scale operating experience of any duration has been obtained. Two facilities highlighted in this report (Lufkin, Texas and Keysville, Maryland) have each been in operation for about one-half a year. The Lufkin facility, processing 3 to 4 dry tons of sludge per week, is the largest to date in this country.

2. The technology is being developed largely by private entrepreneurs. Nearly all vermicomposting operations are directed by individuals associated with the worm-growing industry. Often, they can devote only part-time effort to the operation; as a result, record-keepng is sometimes poor, and results are poorly documented.

3. The S:W (sludge:worm) ratio appears to offer a reasonable engineering design parameter. Valid comparisons can be drawn among different vermicomposting operations only if some consistent indication of performance is used. This can be found in the ratio of sludge weight (dry) consumed per day to earthworm weight (wet), which we have termed the S:W ratio. Examination of loading rates used in six widely-varying vermicomposting operations revealed a reasonably narrow range of performance, as measured by S:W -- 0.12 to 0.27 lb dry solids to lb weight of earthworms per day, with an average of 0.2. This parameter might be an important tool in the study and design of vermicomposting facilities.

4. The worm density to area ratio (W:A) is also an important engineering design parameter. For this report, we used a ratio of 0.4 which corresponds with experience in the worm breeding industry and with vermicomposting at Lufkin, Texas. Higher W:A ratios were also observed, however, and, if proven feasible, use of the higher density ratios would result in reduced area requirements and lower unit costs for the technique. This parameter should be evaluated more fully.

5. Earthworm "castings" might be suitable for sale or distribution as an agricultural soils amendment. Castings derived from sludge, other waste products, and high-quality feeds have been marketed successfully in horticultural potting mixes. The nutrient properties of castings, and their physical structure, appear to make them suitable for agricultural use, provided concentrations of heavy metals in the original sludge are within established limits. Potential product income will probably not play a significant role in cost-effectiveness analysis of future operations.

Other markets that have been proposed for the castings and worms generated in vermicomposting are severely constrained by environmental and public-health considerations and by lack of market capacity.

6. Environmental effects of vermicomposting are similar to those of most other processing methods involving eventual land application. Although the nutrient value of castings lies within a range that could make them of value in agricultural use, the process of vermicomposting does nothing to reduce levels of heavy metals present in the sludge. In fact, the concentrations of these metals -- some of which are toxic at low concentrations to plants or animals -- increase significantly in castings, due to accelerated drying and mineralization effects. Castings will be acceptable for agricultural use when heavy-metals' values in the original sludge are low, as is the case for most of the smaller municipal facilities where vermicomposting might be used.

   There is evidence that the accelerated drying of castings hastens reduction of Salmonella levels. It is not known whether other pathogenic bacteria or viruses in sludge die off more quickly as a result of vermicomposting.

7. Costs of vermicomposting a liquid sludge appear to be competitive for small installations. Operating costs projected from experience at existing vermicomposting facilities are high. Unit costs for vermicomposting of liquid sludge at a daily loading ratio of 0.8 lb/day/sq ft are reasonable -- $105 to $235 per dry ton for a 1-ton-per-day facility. When compared to other options for facilities of the same size, vermicomposting of liquid sludge might prove to be cost-effective.

   The economics of composting dewatered sludge are not as attractive ($360/ton). As currently practised, labor requirements for this process are very high. Mechanization of bed loading and harvesting must be developed and demonstrated. If this is done, vermicomposting of dewatered sludge might prove to be competitive with other process options.

8. Vermicomposting has not yet been demonstrated to be the equivalent of conventional sludge-stabilization techniques. Comparison should be made at demonstration scale between vermicomposting and conventional processes such as digestion and thermophilic composting, in order to scale the performance of vermicomposting in stabilizing sludge and removing pathogens in it. Specific research and development needs are discussed in the next section.

9. Vermicomposting is a feasible process for municipal wastewater sludges. It is currently being used, somewhat successfully, to treat a portion of the sludge generated at about 10 wastewater-treatment plants across the U.S. Although it is in its infancy as a technology, it does show potentially favorable economics as compared to other available processes. Two most-likely applications of the vermicomposting process are:

- Vermicomposting of raw or aerobically-digested liquid sludge pumped directly to wormbeds and applied to an appropriate bedding substrate, such as sawdust, as is practiced at Lufkin, Texas.

- Vermicomposting of a centrifuged or other polymer-conditioned sludge with a solids content of 18 to 20 percent. Dewatered cake would be conveyed directly to the wormbeds, but, since mechanization of this method has not been demonstrated, capacity would be kept to a level requiring only part-time operation.

In either case, the sludge would have to be derived from predominantly domestic wastewater flows. Some provision might have to be made for product sterilization or stabilization, depending on the intended end use of the castings.

Research and Development Needs

Recommendations for additional research in vermicomposting fall under two major headings: basic research and demonstration-scale applied research. Basic research, conducted in laboratories or in conjunction with operation of a demonstration facility, could yield answers to outstanding questions about the optimum conditions of vermicomposting and about the performance of this process as compared to accepted techniques of sludge stabilization. The demonstration-scale research would be applied to optimizing techniques of vermicomposting, determining requirements of scale-up, and developing reliable cost information. Both types of research must be based on design of experiments from which valid inference can be drawn and on rigorous documentation of test conditions and results.

Basic Research

1. The daily loading ratio of sludge-solids:worms (S:W) must be confirmed experimentally as a meaningful indication of performance under constant conditions of vermicomposting. As the ratio depends in part on determination of when conversion of sludge to castings is complete, some consistent, measurable determinant of conversion must be established (e.g., average particle size, percent loss in mass,

original sludge, sludge pH, and effects over time. The availability of metals in castings to uptake by plants and animals should also be documented.

7. Effort should be devoted to identifying the sludge-processing techniques that are and are not compatible with vermicomposting. It is presently believed that anaerobically-digested sludge is toxic to earthworms and that some sludge-conditioning agents (lime, ferric chloride) create unfavorable conditions for vermicomposting.

8. Reliable estimates should be developed for worms' generation time under conditions of vermicomposting. Generation times (rates of population doubling) could vary according to worm density, food (as dry solids), moisture levels, temperature. This research might help to determine optimum worm-residence times in vermicomposting beds and establish whether there is a need to maintain, as an adjunct to the vermicomposting operation, managed beds for breeding and growing new worm stock.

9. Effects of moisture content should be tested in order to establish the limits within which the S:W ratio remains relatively constant. Decline in S:W at low or high moisture levels will indicate practical limits for the vermicomposting operation.

Demonstration-Scale Applied Research

1. Sound documentation of the capital and operating costs of vermicomposting is required in order to help engineers make valid economic comparisons between vermicomposting and conventional sludge-handling techniques. Among the most sensitive cost areas are those associated with structural requirements, labor, and purchase of new worm stock. Requirements in these areas should be documented at a demonstration-scale facility.

2. Mechanization for loading wormbeds with sludge cake might make vermicomposting of dewatered sludge competitive with other stabilization techniques, as present vermicomposting systems of this type are labor-intensive. Additional facilities should be developed for unloading and transporting castings away from the worm beds.

3. Present techniques for harvesting -- separating worms from castings -- include mechanical rotary harvesting and "migration" or "baiting" techniques. The relative efficacies of these methods require evaluation, as do their effects on the economics of vermicomposting. New methods should be examined, including mechanical techniques -- such as slow-moving conveyor systems -- that take advantage of the worms' tendency to migrate to fresh sources of food.

4. Worm growth, development, and reproduction under conditions of full-scale vermicomposting all need documentation. There is not, at present, good evidence that initial worm stocks will be maintained or expanded in vermicomposting beds, given the worms' natural survival times, the periodic disturbance of beds, high food loadings, constant conditions of moisture and temperature, trauma incurred in harvesting, and so forth. Optimum conditions for vermicomposting might not be optimum for worm breeding; in this case, it might be necessary to culture fresh worm stock in undisturbed beds both to make up for normal worm loss and to act as a buffer against system "crashes". Or, depending on the loss rates (if any) projected in demonstration-scale operation, costs of periodic purchase of new worm stock must be considered in the economic evaluation of vermicomposting.

5. From all of these demonstration-scale investigations, the problems and economies of system scale-up should be anticipated. Comparison should be made between laboratory and "real-life" conditions of vermicomposting, in order to put laboratory-based research results in proper context. Results obtained at the demonstration facility should be fully documented to assist in future consideration of vermicomposting as a feasible sludge-management alternative.

percent change in moisture). Test plots can then be established with varying the unit mass of dry sludge per given worm density in order to find out what ratio provides optimum (fastest) conversion, as defined, under constant ambient conditions. This loading ratio will be a key to future design of physical facilities for vermicomposting; from it can be determined the facility's process and area requirements.

2. The S:W ratio will vary according to the conditions of vermicomposting. Although the ratio appears to be independent of sludge moisture content (within a fairly broad range), it will be affected by variables such as temperature, pH, supplemental substrate used, and species of worms used. Optimum conditions of vermicomposting can be determined by testing the S:W ratio obtained under different sets of conditions. Interactions among the variables (including worm density) might help develop specific sets of operating conditions that are feasible for different geographical areas of the United States.

3. Worm density ratios (the W:A ratio expressed in terms of lb worms to unit area of bedding) vary quite widely from one operation to another. Provided that higher worm densities do not interfere with the worms' feeding behavior or degrade product quality, it may be possible to reduce space requirements and unit costs of vermicomposting by increasing the W:A ratio. Research should be directe to optimizing areal densities and establishing clearly their relationship to and effects on the S:W ratio.

4. By far the greatest amount of research work in vermicomposting has been dedicated to the performance of Eisenia foetida and, to a lesser extent, Lumbricus rubellus. Comparisons should be developed on L. rubellus and other species of worms, including Allolobophora chlorotica and Dendrobaena subrubicunda -- both of which occur in nature in areas of high concentrations of organic matter.

5. Although conversion of sludge to castings might hasten the die-off of Salmonella, specific documentation of this effect should be developed. Effects of vermicomposting on other pathogenic bacteria and on viruses should be examined, with relationships drawn between presence of pathogens in the sludge feed and, subsequently, presence in castings at the time of defecation and at intervals over a subsequent "curing" period. If curing is necessary to make vermicomposting the equivalent of other recognized sludge-stabilization techniques that significantly reduce pathogens, a protocol of curing should be established.

6. The exact fate of heavy metals present in sludge fed to worms should be determined. Materials' balances should be performed to determine how much of each metal is taken up (accumulated) by worms and how much is expelled in castings. These rates should be related to other factors, such as concentration and solubility of the metals in the

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Appendix. SITE VISITS

In the course of this investigation, seven vermicomposting operations were visited in order to confirm details of process operation and to view at first hand the techniques and facilities used. Projects currently underway range from the laboratory bench-scale studies conducted at State University of New York (SUNY) in Syracuse to the nearly full-scale experimental vermicomposting techniques being practised at Lufkin, Texas.

The following descriptions, which are based on on-site observations and discussions with facility operators, provide perhaps the best overview of the present state-or-the-art of vermicomposting in the United States.

Keysville, Maryland

Owner/Operator:	Mr. V. Paul France, Arete Vermicomp, Inc., Canton, Ohio/Mr. Robert Bowers, Keysville, Maryland
Date of Visit:	18 October 1979 (Facility not in operation due to flooding at WWTP during previous week)
Sludge Feed:	Aerobically digested sludge, concentrated to 12 - 14 percent solids and air-dried to 17 - 18 percent solids.
Capacity:	Approximately one (1) wet ton per week.

Background. Since June of 1979, sludge trucked from the New Oxford, Pennsylvania wastewater-treatment plant (WWTP) has been processed by vermicomposting at the Keysville facility. Prior to June, Mr. France had for several months obtained and vermicomposted sludge from a WWTP in Laurel, Maryland.

Sludge Processing. Sludge produced at the New Oxford, WWTP is aerobically digested and then concentrated to 12 to 14 percent solids on a Carter belt filter press. A portion of the WWTP's sludge is hauled two or three times per week by open trailer or dump truck to the Keysville site, where is is spread in a 2-inch layer to dry in a semi-enclosed facility. Drying to an estimated 17 to 18 percent solids takes place over two or three days; the sludge is raked periodically to improve drying.

The Laurel WWTP sludge used prior to June, 1979 was an aerobically digested sludge conditioned with polymers and dewatered on vacuum filters. The plant operators' subsequent switch to "hot" (dehydrated) lime and ferric chloride for conditioning proved, however, to make the sludge unsuitable for vermicomposting. Mr. France says the plant's sludge processing will be converted to belt-press operation in December, 1979, at which point vermicomposting of the Laurel sludge will be resumed.

Operation. Once dried, the sludge is hauled in to an enclosed barn and shoveled onto two tables, each of approximate dimensions 30 ft. long and 2½ ft. wide. Aprroximately 300 lb. of sludge is placed on each table and is spread to a uniform depth of 1½ to 2 inches.

The bottom of each table consists of common windowscreen supported by chicken wire and wooden cross-braces. The open bottom provides increased surface area, helping to dry the sludge further and to keep it in an aerobic condition.

Approximately 100 lb. of earthworms, Eisenia foetida, are weighed out and distributed evenly over the sludge in each table. The worms quickly migrate into the sludge and reportedly convert all of the sludge to castings within a 48-hour period. A black plastic cover is placed over the sludge bed for approximately 6 to 8 hours during the 48-hour vermicomposting process, in order to ensure that worms feed at the surface of the sludge mass.

Conditions of Culture, Temperatures in the vermicomposting room are reportedly maintained between 18°C and 22°C, although the temperature was 14°C at the time of the site visit. Temperatures below 16°C or above 26°C reportedly slow the vermicomposting process by 10 percent or more.

Higher worm:sludge ratios have been attempted as a means of reducing vermicomposting time, but the result has been a wetter and less manageable castings product. Lower ratios increase vermicomposting time.

Fresh worm stock is maintained in semi-enclosed and enclosed structures using standard techniques of vermiculture.

Processing of Products. After 48 hours (or when conversion is determined by inspection to be complete), earthworms and castings are removed manually from the beds and placed in a cylindrical rotating screen. Castings fall through the screen into tubs, while earthworms travel through the length of the drum for collection and recycling into another sludge bed. Some worms are lost in the harvesting process, due to their small size or to trauma, but these losses are estimated at only one percent per week.

At present, castings are being stockpiled for future use.

Marketing of Products. No products of the Keysville operation are currently being marketed. Mr. France reports, however, that he is marketing in Ohio a "Nutri-Loam" potting soil, that contains castings produced at his similar vermicomposting operations at Gallion and Canton, Ohio. Castings make up about 15 percent of the Nutri-Loam mixture, by volume; other ingredients include Vermiculite, peat moss, Perlite, sand, kelp and other ingredients. The product, selling for $1.75 per four-quart bag, has been available in selected supermarkets and garden shops since August. Mr. France is currently setting up distributorships in Ohio and several middle-Atlantic seaboard states. He also plans to start producing Nutri-Loam at the Keysville facility. Mr. France states that his long-term interest is in development of an agricultural product suitable for use in bulk.

Research and Analysis. Most of the process development underway at Keysville is focused on optimizing the conditions of sludge vermicomposting. Analyses of sludge and castings constituents have reportedly been carried out by laboratories at Pennsylvania State University and the University of Montana (one analysis of sludge constituents is included in Section 2 of this report, in Description of Sludge Feed). Dr. Rufus Chaney of the U.S. Department of Agriculture has also obtained a castings' sample for analysis.

Louisville, Colorado

Owner/Operator:	Mr. Jim McNelly, Planet Earth Worms
Date of Visit:	14 September 1979
Feed:	Composted yard wastes (grass clippings)

Background. Mr. McNelly has been doing research in vermicomposting for the last five years; he produces and markets several organic materials, one of which includes castings.

Material Used and Operation. Composted grass-clippings and other yard wastes are obtained from the City of Boulder, which operates a windrow-type process. The compost is fed to earthworms maintained in an indoor windrow-type facility in order to produce castings. Neither sludge nor municipal solid waste have been utilized at Louisville.

Marketing of Products. A "NaturSoil" potting soil containing earthworm castings (15 percent by weight) is packaged and marketed. The castings include those produced at Louisville as well as others purchased from worm growers who have gone out of business. Other ingredients include: domestic and Canadian peat moss, limestone, bark mulch, topsoil, sand, vermiculite and diatomaceous earth.

The suggested retail price is $1.75 per 8-lb package, although prices throughout Colorado range from $1.40 to $2.50. The mixture is also sold in bulk to greenhouses for $280 per truckload (approximately 8 cu yds). McNelly sells to brokers, who distribute the product to supermarkets, health food stores, retail plant stores and hardware and garden shops.

Research. Most of the experience at Louisville is with marketing. Research has been conducted on capsule production using a slurrying/screening technique. Research is geared toward developing a market for earthworms as a future protein source.

Lufkin, Texas

Owner/Operator: City of Lufkin, Texas/Mr. Edward Green, Early Bird Farms (project consultant)

Date of Visit: 7 September 1979

Sludge Feed: Primary and waste activated sludge at 3.5 to 4.0 percent solids

Capacity: 1,800 gallons per day

Background. This demonstration project, still in the start-up phase at the time visited, involves vermicomposting of a portion of combined raw sludges from the 4-mgd City of Lufkin WWTP. The City's primary objective is to reduce total sludge-management costs and not to market a castings or earthworms product.

Sludge Processing. The City of Lufkin operates a secondary wastewater-treatment facility that processes about 4 mgd of domestic and industrial wastewater. The wastes are of high strength, due to flows contributed from two poultry-processing facilities. Primary and waste activated sludges are combined prior to thickening in a gravity thickener; a small portion of the thickened sludge is then pumped to the vermicomposting operation at 3.5 to 4.0 percent solids. Most of the sludge from the facility is heat treated and vacuum filtered prior to landfilling.

Operation. The City has constructed 12 experimental vermicomposting beds. Each bed is of dimensions 20 ft. by 95 ft., or 1900 sq. ft. in area, and each is covered with a plastic roof over a steel frame. The roof consists of two layers of plastic, an inner layer of clear plastic and an outer black layer that can be removed during the winter to create a greenhouse effect.

At the time of the site visit, six of the 12 beds were in operation. Within the beds are a 2-in. deep layer of sawdust and the earthworms. Since the site visit, the bed depth has been increased to about 8 inches. The City has purchased 4800 lbs of worms at an average cost of $1.50/lb and has advertised for another 5200 lb. The earthworm density is approximately 800 lb per 1900 sq ft (0.42 lb/sq ft).

The earthworms feed near the top few inches of the beds, and castings eventually become compacted near the bottom of the beds.

Approximately 300 gallons of 3.5 to 4.0 percent sludge is sprayed onto each bed each day; the solids loading rate is approximately 100 lb/1900 sq ft. When all 12 beds are in operation, about 10 percent of the plant sludge will be processed by vermicomposting. The sludge spraying system is automatic and consists of a central header with laterals along each side of the 12 beds. A spring-loaded valve is used to distribute the sludge along the beds.

Processing of Products. Earthworms and castings have not yet been separated but have simply been left in the six active beds. Although mechanical rotary screen is available for separating worms from castings, the project consultant has recommended that the City use instead a baiting technique for moving earthworms. This technique would consist of windrowing a finished bed and placing fresh sludge and sawdust adjacent to the windrow. The earthworms would migrate to the better food source, leaving a windrow of finished castings. The technique should be less costly than mechanical-screen harvesting and might also present less risk of trauma to the worms.

Marketing of Products. No attempt has been made to market castings or worms.

Research and Analysis. Although only in the start-up phase, the Lufkin facility offers a potentially valuable source of information on vermicomposting, provided that the research is carrried out in a manner that will produce good documentation of the results.

Ridgefield, Washington

Owner/Operator: Mr. J. "Red" McClarran, American Organics, Ltd.

Date of Visit: 13 September 1979

Sludge Feed: Raw sludge at 2 percent solids

Background. American Organics is a firm that markets several organic agricultural/horticultural materials, some of which are made from earthworms castings. Reportedly, over the last several years, some 400 tons of horse manure and other manures, paper-mill sludge and cedar-toe sawdust (from the production of cedar shingles) have been vermicomposted at the Ridgefield facility. Mr. McClarran has also conducted pilot studies on the vermicomposting of municipal sludge.

Most of the experience at Ridgefield is related to product packaging and marketing. In fact, a large portion of the castings used in the firm's potting mix is bought from wormgrowers who have gone out of business. There is not a great deal of documentation of results obtained using various types of organic materials.

Operation. Mr. McClarran has constructed several test plots using various bedding and feed materials. In one field plot, organic materials were placed in windrows approximately 10 feet wide and 1 foot deep (during the cold winter months, the depth is increased to 3 or 4 feet). To date, approximately 750 linear feet of windrows have been constructed. Since July 1979, approximately 80,000 gallons of raw sludge at 2% solids (6.5 dry tons) has been applied to the windrows. Sludge is trucked in two or three times per week from the Ridgefield, La Center and Woodland

WWTPs. The liquid sludge is either sprayed on the windrow of the materials described above or discharged at the higher end of a 150-ft. -long windrow. The liquid sludge flows by gravity along the length of the windrow.

The loading rate is approximately 20 gallons/ft. during favorable weather and 3 gallons/ft. during winter conditions.

The present operation is very labor-intensive, but AO has begun aerating the windrows mechanically, using a tractor that pulls a rotating comb. The comb breaks up the top 4 to 6 inches of material.

Three types of earthworms are present: night-crawlers, red worms, and common garden worms. Predators are reportedly not a problem. Some flies are present, and slight odors are noted after windrow aeration. Leachate is not a problem, due to clay soils at the site.

Processing of Products. AO has not separated castings from the windrows to which sludge has been applied. The Southwest Washington Health District does not presently allow marketing of this sludge-derived material.

Castings from non-sludge windrows are sterilized to control nematodes and other pests, prior to use in a potting mix. According to Mr. McClarran, three sterilization methods are available: steam, open flame, and methyl bromide.

The material sells for $3 to $4 per eight-quart bag in grocery and department stores and lumber suppliers and nurseries. A 12-quart bag is also sold.

Marketing of Products. Approximately 100,000 lbs. (100,000 quarts) of "Black Gold" potting mix have been marketed. "Black Gold" consists of earthworm castings, perlite and Canadian peat moss.

San Jose, California

Owner/Operator:	City of San Jose/Mr. Jack Collier, Collier's Earthworm Compost Systems, Inc. (CECOMS)
Date of Visit:	11 July 1979
Sludge Feed:	Anaerobically-digested sludge, dried in a lagoon for several years to about 80 percent solids
Capacity:	20-25 cubic feet per week

Background. Several years ago, Mr. Collier approached the City of San Jose with a proposal to compost sludge using earthworms. He was granted access to two 3½-acre sludge lagoons at the 160-mgd San Jose-Santa Clara water pollution control plant. He also applied for and received a grant from the National Science Foundation to pilot a vermicomposting process.

Sludge Processing. The sludge is an anaerobically digested sludge that has been dried two or more years in the sludge lagoons to an 80-percent solids content.

Operation. One of the lagoons was first stripped of vegetation (tumbleweeds had grown to a five-foot height). About five inches of dried sludge was then scraped from the lagoon and formed into windrows, each of dimensions 5 feet wide, 50 feet long and about 15 inches deep.

The sludge was wetted with potable water to an unknown moisture content and covered with a canvas to retain moisture. A V-shaped trench was cut along the top of the windrow and approximately 125 pounds of earthworms (E. foetida) were distributed over the 50-foot length, or somewhat less than 0.5 lb of worms per square foot of surface area. After a few days, the worms migrated out into the sludge cake. After three or four months, the process was considered accomplished.

Most windrows that have been constructed have never been harvested. In fact, some do not contain adult worms, which reportedly have abandoned the windrows in search of a new food source. During the last several months, Mr. Collier has been attempting to persuade the City to authorize the use of 50 acres of lagoons for a full-scale production facility. Vermicomposting has not been studied as an alternative by the City's consultant in its current 201 facilities plan for sludge management.

The vermicomposting process developed by CECOMS is based entirely on the San Jose experience. There is no control parameter to ascertain when the material is considered composted. Mr. Collier stated that the density of earthworms seeded in thh windrow might be doubled from 0.75 lb/cu. ft. to 1.5 lb/cu. ft., but what corresponding decrease in retention time might be achieved is not known.

Processing of Products. Some materials have been removed from windrows to a rotating-screen harvester, where castings and worms were separated.

Marketing of Products. Mr. Collier plans to market the castings as a potting soil.

Research and Analysis. Castings produced at the San Jose facility have been analyzed by an independent laboratory; some of the results are reported in Section 4 of this report.

Syracuse, New York

Institution/Principal Investigators:	State University of New York, College of Environmental Science and Forestry/ Dr. Roy Hartenstein, Dr. Edward F. Neuhauser
Date of Visit:	4 October 1979
Sludge Feed:	Primarily aerobically digested, air-dried to 11 percent solids; also aerobically digested sludge centrifuged to 11 - 20 percent solids
Capacity:	Laboratory and pilot-scale research

Background. Since July 1976, work by Dr. Hartenstein and his associates has been funded by successive grants from the National Science Foundation. The work also received in 1979 joint funding by the State of New York. The research has concentrated on laboratory experiments using *E. foetida* feeding on sludges obtained from local wastewater-treatment facilities. Some recent research has covered the biology and ecology of *Eudrilus eugeniae* (African nightcrawlers) and pheretemoid worms.

Research and Analyses. Two compendia have been published under National Science Foundation grants: "Utilization of Soil Invertebrates in Stabilization, Decontamination and Detoxification of Residual Sludges from Treatment of Wastewater", June 1977, and "Utilization of Soil Organisms in Sludge Management", June 1978. The latter contains papers presented at a SUNY-hosted conference. Numerous additional papers have been published or submitted for publication in technical journals; the following representative titles indicate the scope of research completed or underway at SUNY:

"Effects of Different Sewage Sludges on Some Chemical and Biological Characteristics of Soil", M.J. Mitchell *et al* (14)

"A Study on the Interactions of Enzymes with Manures and Sludges", L. Theoret *et al* (17)

"A Progress Report on the Potential Use of Earthworms in Sludge Management", R. Hartenstein *et al* (107)

"Growth of the Earthworm *Eisenia foetida* in Relation to Population Density and Food Rationing", E.F. Neuhauser *et al* (108)

Reproductive Potential of the Earthworm *Eisenia foetida*", R. Hartenstein *et al* (116)

"Physicochemical Changes Accompanying the Conversion of Activated Sludge into Castings by the Earthworm *Eisenia foetida*", R. Hartenstein *et al* (120)

"Materials Supportive of Weight Gain by the Earthworm Eisenia foetida in Waste Conversion Systems", E. F. Neuhauser et al (109)

"Composition of the Earthworm Eisenia foetida and Assimilation of Fifteen Elements from Sludge during Growth", R. Hartenstein et al (124)

"Soil Organisms and Stabilizing Wastes", D. L. Dindal (16)

"Conversion of Sludges into Topsoils by Earthworms", M. J. Mitchell et al (15)

Because the SUNY research is carried out under carefully controlled conditions in small-scale laboratory tests, it is particularly valuable in helping to establish a reliable base of information on chemical, biological and physiological parameters of vermicomposting. Two qualifications must be attached, however. First, the SUNY results might not be directly applicable to full-scale vermicomposting operations in the field. The E. foetida used in SUNY experiments are acclimated to the constant 25°C temperatures at which the experiments are run. Performance of individual worms in glass dishes might be either improved or depressed in larger beds with high densities of worms. Second, we are aware of no comparable research being conducted in the United States; therefore, there is lacking a measure of competition and criticism that might improve the accuracy and applicability of the SUNY findings.

Among the particularly pertinent results obtained at the SUNY laboratory, Dr. Hartenstein and his associates determined in 1977-78 that anaerobic and anaerobically digested sludges are unsuitable for vermicomposting. Freshly obtained, anaerobically digested sludge is toxic to E. foetida; even if aged prior to vermicomposting, the sludge still fails to support a thriving worm population.

In laboratory experiments at 25°C, E. foetida consume about 0.5 g of aerobically digested of raw sludge per day per gram of worm weight (wet). A typical experiment shows that 25 g of earthworms require four weeks to consume a 350 g sludge sample.

Titusville, Florida

Owner/Operator:	Ms. C. Carlson
Date of Visit	6 September 1979
Sludge Feed:	Fresh sludge, thickened to 10 percent solids
Capacity:	4,000 to 6,000 gallons per week

Background. This facility has been operated on an experimental basis for the past two years. The operator is not interested in marketing of products, but rather in demonstrating the feasibility of vermicomposting for sludge management. For the most part, experiments are conducted without data collection or documentation of findings.

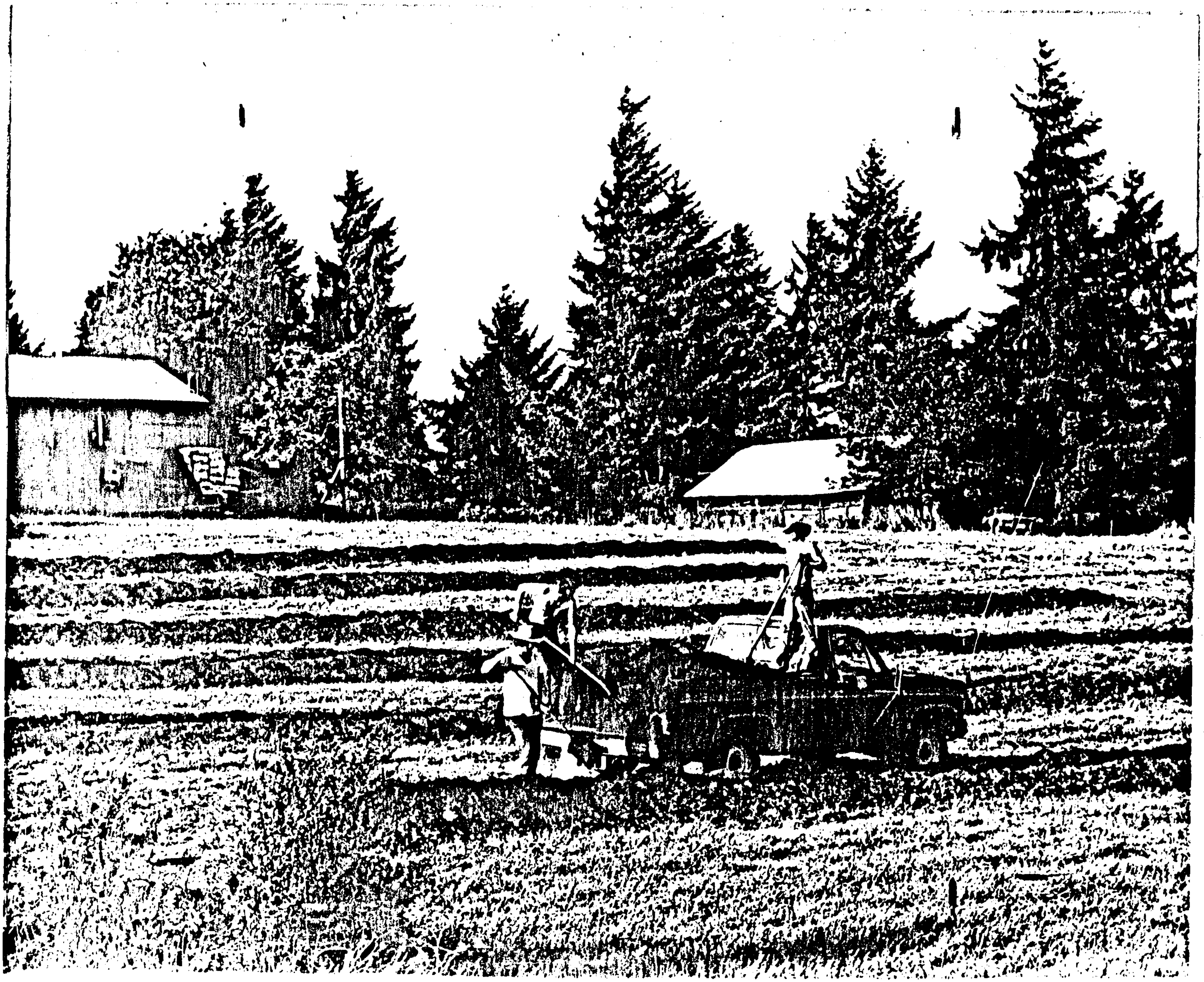
Feed Materials. A variety of organic feed materials has been tried, including mixtures of cow manure and sawdust, sludge and sawdust, and sludge and cardboard. Sludge is obtained from the City of Titusville WWTP at 3 percent solids; it is delivered to the site two or three times per week in a 2000-gallon tank truck. Sludge is discharged to a ditch adjacent to the facility, where it is allowed to thicken to about 10-percent solids.

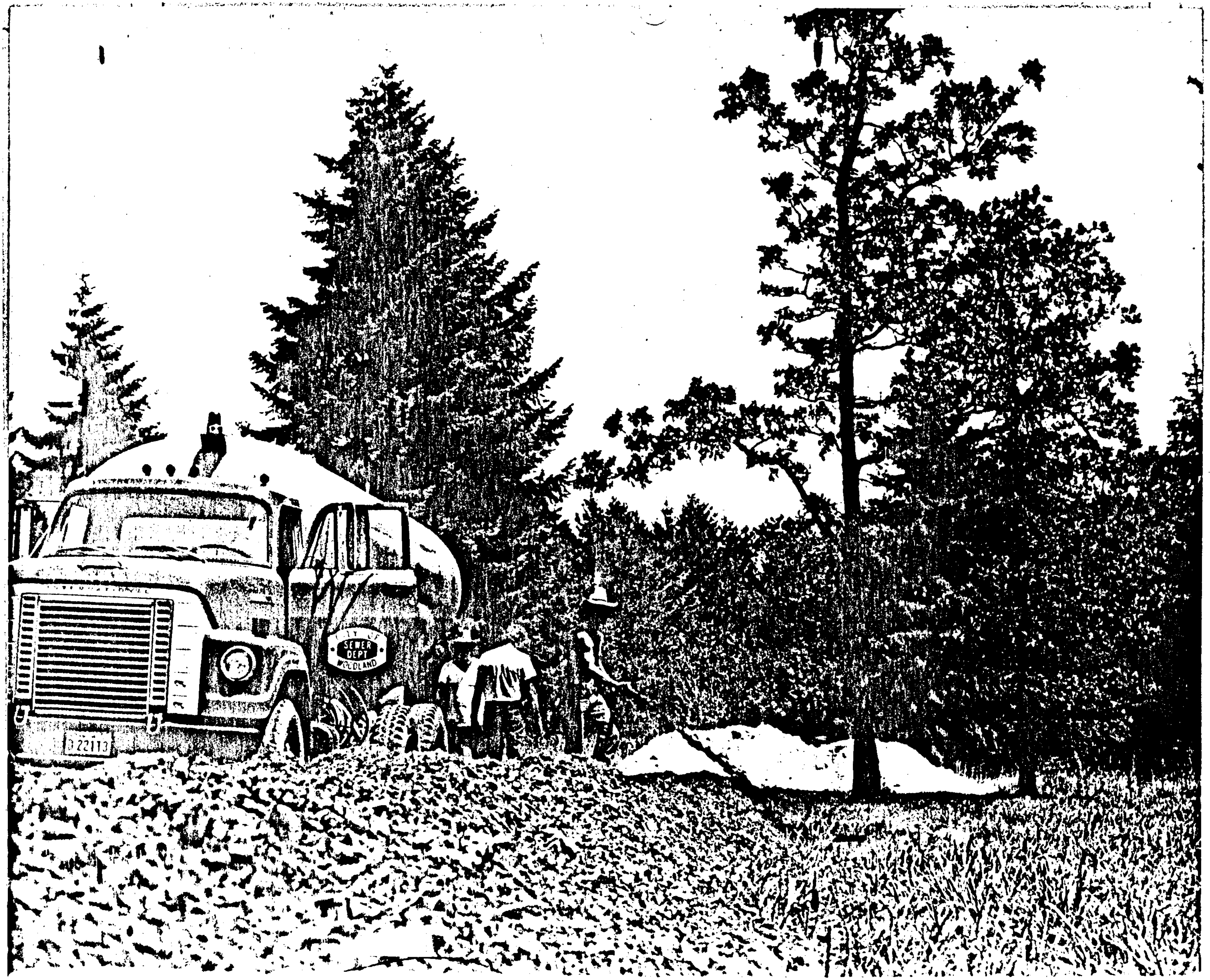
Operation. Three types of earthworm beds have been used: two 10-ft by 60-ft inground beds, four 3-ft by 8-ft concrete beds and three 4-ft by 9-ft wooden beds. The larger, in-ground beds reportedly are the most successful. Bed depths range up to 1 foot.

Sludge is manually removed from the storage ditch and transported by wheelbarrow approximately 50 feet to the worm beds. The worm beds have an initial layer of cardboard placed in them. A 1-inch layer of sludge cake is shoveled onto the cardboard in the beds. This is repeated several times to create a 3- to 4-inch layer of fresh material.

The worms in the bed reportedly migrate up from lower, older layers to feed on the new cardboard-sludge mixture. Consumption of this mixture reportedly takes place in six to eight weeks, depending on weather conditions and season, and as judged by observation. In warmer weather, up to twice as long may be required for conversion; in cooler weather, as little as half as much time is required. Cool-weather temperatures in Florida result in bed temperatures in the 15°C range, which are preferred by earthworms to hot weather conditions (27°C and higher).

Processing and Marketing of Products. The operator is not separating earthworms from castings; wormbeds are simply used to store the finished product.

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