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Vermitechnology for Organic Waste Recycling

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5.1 Introduction

Solid waste management is among the biggest challenges, in urban as well as rural areas, in developed as well as developing nations. Unprecedented population growth and intensive industrial and agricultural activities have led to both increased quantities and changes in the composition of solid waste. As a result solid waste is generally improperly handled and indiscriminately dumped and/or burned in open areas and landfills. These practices have adverse impacts on water, air, and soil quality and pose serious health hazards to the surrounding communities.

According to an estimate by the Central Pollution Control Board, New Delhi, the organic fraction constitutes ≈40% of the total municipal solid waste generation in most developing countries. The major components of the organic fraction are food waste, human and animal excreta, sewage sludge, leaf litter, agricultural and agro-industrial waste, and paper and packaging waste. Most of it usually goes to unscientifically managed landfill sites and becomes a nuisance for the surroundings. The organic fraction in landfills is broken down by microorganisms, posing two-way hazards. On one hand, the decomposition of organic waste forms a liquid "leachate," which contains chemical and biological contaminants. This leachate presents a serious hazard if it contaminates the water table or other water courses. On the other hand, methane gas, a potential greenhouse gas, is generated.

Considering the huge organic fraction of municipal solid waste, composting and vermicomposting that consume organic wastes are technically ideal to manage these categories of waste. These waste decomposition methods could provide opportunities for reducing pollution as well as improving soil fertility in agricultural fields. These processes may also be economically and environmentally suitable options in comparison to other waste management strategies because both processes reduce the bulk volume of organic waste materials, eliminate the risk of spreading pathogens, and produce a humus-like material, which can be used to improve and maintain soil fertility.

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Composting is carried out by heterotrophic microbial populations, viz., bacteria, fungi, actinomycetes, etc., that break organic waste into carbon dioxide, water, minerals, and a stabilized product called compost in a thermophilic temperature range. Several methods of composting, viz., windrow, in-vessel, etc., are practiced and any of the methods can be applied in given situations. Decontamination of the compost is achieved through the early thermophilic phase of composting, when temperature reaches up to 70°C. During the mesophilic phase the remaining organic compounds are degraded at a slow pace in a process similar to humification in soils. The process can effectively reduce the waste volume by 40–50%. However, the major limitations associated with composting are longer duration of the process, loss of nutrients during the process, loss of beneficial microbes during thermophilic phase, etc. [1].

In past years, many studies and reports have proved that vermicomposting of organic waste by earthworms is the more economically and ecologically preferred waste recycling method over traditional microbial composting. The process of vermicomposting is conducted in a narrow range of temperature (25–40°C), near neutral pH (6.5–8.5), and high humidity (60–70%) to sustain a large population of earthworms. It degrades the organic waste in about 2–4 months and the end product is an odorless, disinfected, and highly nutritive vermicompost, which is suitable for organic manuring of agricultural soil. Moreover, it is known that earthworms release coelomic fluids in which mucocytes, vacuolocytes, granulocytes, and lymphocytes are present, which kill the bacteria and parasites present in the waste, thus making the vermicompost odor and pathogen free [2]. Significantly, vermicompost is considered an excellent product of homogeneous and odorless nature, which is rich in microflora and tends to hold more plant nutrients over a longer period.

Vermicomposting is one technology that can be used at small (household level) to very large (several households, village, or an entire city) scales. In this chapter, a detailed description of the vermicomposting process, various process parameters, suitable earthworm species, effective waste management, and potential application of the product to plants is presented.

5.2 Vermitechnology for Organic Waste Recycling

Vermitechnology is a combination of various processes to break down and stabilize organic waste materials through the joint action of earthworms and microorganisms in an aerobic environment. Generally, it involves ingestion, digestion, and absorption of organic waste carried out by earthworms in a mesophilic temperature range followed by excretion of castings through the worms' metabolic system. At the end, a dark-colored, homogeneous, and stable product known as vermicompost is produced, with high levels of plant nutrients compared to the parent material. Vermitechnology is different from the term "vermiculture" in the sense that the prime motive in the latter process is the rearing of earthworms on organic materials for mass propagation, rather than waste reduction and vermicompost production.

Based on the earthworm's activities, the vermicomposting process can be divided into two phases:

1. *the direct vermicomposting phase*, in which earthworms ingest, digest, and assimilate the organic materials and modify their physicochemical and microbial properties, and
2. *the indirect maturation phase*, in which microorganisms already present in the organic feed material or propagated under the existence of earthworms decompose the processed materials until the end even after the earthworms are removed from the process [3].

The earthworms have dual actions in the process: they secrete enzymes to degrade the organic waste material as well as proliferating the growth of microorganisms in the waste material. It is estimated that about 5 kg of earthworms can convert 1 ton of organic waste into about 0.5 ton of vermicompost in just 30 days if provided the optimum temperature (25–40°C) and moisture (60–70%). And the initial amount of organic waste is reduced by 30–40% in the form of vermicompost at the end of process. Almost every nontoxic organic solid waste, such as animal dung, agricultural residues, sugarcane industry waste, food-processing industry waste, paper–pulp industry waste, and sewage sludge, makes good raw material for vermicomposting. In this way, the use of vermicomposting has two-pronged benefits: on one hand, solid waste pollution is reduced; on the other, waste is converted into manure.

5.3 Earthworms

About 3320 distinct species of earthworms have been identified in the world, each with unique physical and behavioral characteristics [4]. These species have been grouped into the following three categories, descriptive of the area of the natural soil environment in which they are found and defined to some degree by environmental requirements and behaviors [5–7].

1. **Epigeic**: The epigeic earthworms do not inhabit the soil; rather they live in and consume surface litter, plant debris, and decaying organic matter. They ingest the organic matter and provide a microenvironment for the establishment of decomposing microorganisms. The major advantage of epigeics is that they do not burrow into the soil and are therefore more easily contained within vermicomposting systems than other types of earthworms. They can be raised at several levels of production, from small-scale bins to large-scale vermicomposting of agricultural, municipal, and industrial organic solids. Examples are *Eisenia fetida*, *Eisenia andrei*, *Eudrilus eugeniae*, *Perionyx excavatus*, and *Drawida modesta*.
2. **Endogeic**: These species are not very suitable for vermicomposting but play a major role in soil formation processes such as soil mixing and aeration because of

their burrowing nature, as they build continuous ramifying horizontal burrows in the soil more or less enriched with organic matter. Examples are *Octochaetona thurstoni*, *Allolobophora caliginosa*, and *Allolobophora rosea*.

3. **Anecic**: These species are very supportive in decomposition and distribution of organic matter in soil and improve soil structure and texture by nutrient recycling. These earthworms construct and live in permanent burrows in deep soil layers and bury organic matter, mostly plant litter, into their burrow from the surface. These have comparatively moderate reproduction rates and long life spans. Examples are *Lampito mauritii*, *Lumbricus terrestris*, and *Octochaetona serrata*.

The earthworms should possess a few characteristics to become efficient vermicomposting workers, These mainly include capability to colonize in organic waste; high consumption, digestion, and assimilation rate; high growth rate; high reproduction and cocoon production so that organic matter conversion is fast; and wide tolerance to climatic temperature variations. It is well established that epigeic species of earthworms are widely used for the purpose of vermicomposting of various wastes [8]. Among these, *E. eugeniae*, *P. excavatus*, and *E. fetida* have great potential as waste decomposers [9]. A brief description of these is as follows:

Eudrilus eugeniae, a native of equatorial West Africa, is commonly known as the night crawler. It grows faster than other species, accumulating mass at the rate of 12 mg/day. Mature individuals can attain body weight up to 4.3 g/individual. Maturity is attained over a period of 40 days and, a week later, individuals commence cocoon production (on average one cocoon per day). Life span in the laboratory has been estimated from 1 to 3 years. The temperature tolerance of *E. eugeniae* is lower than that of *E. fetida*.

Perionyx excavatus is highly adaptable and can tolerate a wide range of moisture and quality of organic matter. Average growth rate of *P. excavatus* is 3.5 mg/day and body weight (maximum) is 600 mg. Maturity is attained within 21–22 days and reproduction commences by the 24th day, with one to three hatchlings per cocoon.

Eisenia fetida, popularly known as the red wriggler, red worm, tiger worm, etc., is perhaps the most widely used earthworm for vermicomposting. The species is also used widely for various toxicological studies as a test worm. Mature individuals can attain up to 1.5 g body weight. Each mature worm on average produces one cocoon every third day and from each cocoon emerge one to three individuals on hatching within 23 days. The average life of a worm is 1–2 years [10].

A literature survey shows that *E. fetida* is the most popular and preferred species because of its wider tolerance for temperature than *E. eugeniae* and *P. excavatus*. *Eisenia fetida* can be cultivated in areas with higher temperature (as high as 43°C) as well as lower temperature (<5°C) [11,12].

Moreover, *E. fetida* grows rapidly, feeds on almost any organic matter, can be easily handled, and has a high reproductive rate, and there is more known about its biology than any other species [13,14].

5.4 Role of Earthworms in Vermicomposting

Hickman and Reid [15] reported that earthworms are aerators, grinders, crushers, and degraders of solid waste [16,17]. As the earthworms move throughout the waste material, their resulting burrows act as aeration points. In addition, the earthworms ingest and digest waste material, resulting in its mechanical breakdown during passage through their muscular gizzard. Then, it passes to the intestine of the worm and is decomposed by various enzymes present in the intestine as well as by the enzymes of the ingested microorganisms [18]. The size of organic matter is reduced by 25—30% during vermicomposting [19] and surface area is increased [20]. The complex compounds present in the waste material are converted into simpler ones and, in turn, the plant nutrients contained in the material, such as nitrogen, phosphorus, and potassium (NPK), are changed into forms that are more soluble and more available to plants than the parent organic material [1]. During vermicomposting the earthworms have a mutualistic relationship with their ingested microorganisms, which decompose the organic matter present in their food [21]. Thus, the manurial value of the vermicompost is the result of combined actions of earthworms and microorganisms.

5.5 Various Stages in the Vermicomposting Process

The vermicomposting process takes place mainly in the mesophilic temperature range (20—35°C). The process of vermicomposting can be divided into four stages.

5.5.1 Precomposting Stage

The precomposting of organic waste is essential to make the waste semicomposted so it becomes palatable to the worms. The waste should be free of toxicity, excessive heat, urine, salts, ammonia, alkali, alcohol, pesticides, medicines, antibiotics, etc. [22,23]. This stage includes composting of waste under natural conditions for 3—4 weeks depending on the type of waste. During this phase, readily decomposable compounds are degraded and the potential volatile substances (such as ammonia gas) are eliminated, which may be toxic to earthworms.

5.5.2 Mixing Stage

This stage includes mixing of various types of organic waste materials either to make the feed acceptable to the worms or to get a good quality vermicompost. Several organic wastes such as paper—pulp mill sludge, sugar mill sludge, textile mill sludge, etc., have undesirable characteristics for earthworms but these may be ideal feed if amended with other suitable waste materials [24]. Crop residues containing higher cellulose contents and similar derivatives could be mixed with animal dung, which has high nitrogen content, to make a favorable feed for earthworms [25,26]. However, this stage can be ignored if the organic waste is favored by the earthworms in its original form.

5.5.3 Vermicomposting Stage

This is the actual process in which worms are fed on waste in different types of bins and beds for about 8—10 weeks. During this stage, the worms enhance microbial activities in the waste and decompose and stabilize it for the formation of vermicompost. Various biochemical and physical changes such as in pH, NPK contents, etc., occur in this stage through the joint action of earthworms and microorganisms. During this stage optimum moisture and temperature should be maintained to have maximum worm activity.

5.5.4 Maturation Stage

The vermicompost maturity is an important factor for its quality assessment. The stabilization and maturation of vermicompost may take 3—4 weeks. The vermicompost is ready to use once it is matured. The nutrient availability to plants from organic manure is closely related to its maturity. Matured organic manure is well balanced in nutrients (N, P, and K), with low C/N and C/P ratios, which indicates a slow rate of nutrient release, whereas in the case of unstabilized and fresh organic waste, these ratios are higher, which in turn limits the microbial growth and ultimately impedes or even prevents decomposition of the waste [27].

5.6 Influence of Process Parameters on Vermicomposting

Various process parameters that may affect the vermicomposting have been encapsulated in Table 5.1. These are described next in detail.

5.6.1 Moisture Content

Adequate moisture content in vermicomposting systems is critical for worm and microbial activity because earthworms breathe through their skin. Sixty to eighty percent moisture has been reported to be optimum during vermicomposting [28],

Table 5.1 Process Parameters for Vermicomposting

S. No.	Factor	Optimum Conditions
1	Moisture content	60—80%
2	Temperature	15—28°C
3	pH	6.5—8.5
4	Aeration	• Frequent turning of waste • Excessive moisture should be avoided • Greasy and oily wastes should not present
5	Feed quality	• Should be free of toxic, nonbiodegradable waste • Should be free of salts • Should have optimum C/N ratio
6	Light	Earthworms are light-sensitive, so vermicomposting bins should either be placed in dark places or be covered

though physical and chemical differences in waste materials may cause slight variations. Excessive moisture may cause anaerobic conditions in vermibins and vermibeds, whereas less moisture in the waste material may be lethal to the worms [11].

5.6.2 Temperature

The optimum temperature range during the vermicomposting process is 15–28°C. The earthworms exhibit multifaceted responses to changes in temperature. During winter the temperature should be maintained above 10°C and in summer the temperature should be maintained below 35°C [29]. At very low temperatures, the metabolic activities of worms are reduced and they are not able to reproduce [20]. Dominguez and Edwards [22] have deciphered that the unfavorable effect of higher temperatures (above 30°C) on most of the species is not entirely a direct effect. They reported that enhanced chemical and microbial activities in the waste at high temperatures tend to consume the available oxygen, with negative effects on the earthworms. Further, tolerances and preferences for temperature vary from species to species.

5.6.3 pH

The acceptable pH range, suitable for earthworm and microorganism activity, is 6.5–8.5 in vermicomposting systems. During vermicomposting the pH value of the waste undergoes considerable changes. An initial phase characterized by a low pH is often observed during vermicomposting of waste. This is due to the formation of carbon dioxide and volatile fatty acids during the initial stages. With the subsequent evolution of CO_2 and utilization of volatile fatty acids, the pH begins to rise as the process progresses [30].

5.6.4 Aeration

As the earthworms are aerobic organisms, oxygen is crucial for vermicomposting. Factors such as higher levels of fatty/oily substances in the feedstock or excessive moisture may render the conditions anaerobic in the vermicomposting system. Earthworms are very sensitive to anaerobic conditions and their feeding activities might be reduced under these conditions [20]. They may also be affected by the formation of toxic substances (eg, ammonia) produced under such conditions. This is one of the main reasons for not including meat or other fatty/oily wastes in worm feedstock unless they have been precomposted to break down the oils and fats.

5.6.5 Feed Quality

A suitable quality of feed material for earthworms is of the utmost importance to have a successful vermicomposting system. Earthworms take their nutrition from organic materials, from living microorganisms, and by decomposing macrofauna. The amount of waste that can be consumed daily by earthworms depends on a number of factors such as waste particle size, decomposition state of the waste, C/N ratio of the waste, salt content in the waste, etc. Small waste particle size ensures the worms will speed up the process by fast decomposition. Further, the small particle size allows proper aeration through the pile of waste material and its availability to the worms. The quantity of food taken by a worm varies from 100 to 300 mg/g body weight/day [31]. Worms are very sensitive to salts. The feed should have less than 0.5% salt content [32]. Feed should not contain any nonbiodegradable or toxic substance (e.g., inert materials, plastics, glass, metal objects, detergents, pharmaceuticals, etc.) that poses a risk either directly to the earthworms or through their metabolic products [33]. The C/N ratio of feed material affects the earthworms' growth and reproduction. The optimum C/N ratio for vermicomposting is 30:1. If the C/N is too high or too low, waste degradation becomes a slow process. Several studies have proved that the C/N ratio in soils with litter may be brought down to less than 25:1 by the intervention of earthworms [34]. If the organic feed material is poor in nitrogen and the C/N ratio is high, microbial activity decreases in the feed substrate [35].

5.6.6 Illumination

Earthworms are photophobic by nature [35], so they should be kept away from light. They experience partial-to-complete paralysis from short exposure from sunlight and long exposures are lethal to earthworms. They use light-sensitive skin cells concentrated at the front end of their bodies to sense light and move away from it.

5.6.7 Microorganisms and Enzymes

The earthworms interact with microorganisms (fungi, bacteria and actinomycetes, phosphate solubilizers, nitrifiers, etc.) in waste although the interactions are totally dependent upon the earthworm species. Increased microbial numbers and activity have been reported during the vermicomposting process. This may be related to passage of microorganisms present in the waste through the earthworm gut, as well as their promotion therein, and the "awakening" of dormant gut flora. Several studies have found bacterial species like *Pseudomonas*, *Mucor*, *Azoarcus*, *Paenibacillus*, *Spiroplasma*, *Alcaligenes*, *Acidobacterium*, etc., associated with the gut and casts of the earthworms. These bacterial species have been found to degrade several categories of organic wastes. It is known that preexposure or preinduction of microorganisms to organic matter can result in subsequent increased degradation rates.

Chemically organic wastes are very complex and their complete stabilization requires enzymatic action. The worms secrete enzymes in their gizzard and intestine that bring about rapid biochemical conversion of the cellulosic and the proteinaceous materials in the organic waste. Some of the main enzymes involved in the vermicomposting process include cellulases, which depolymerize cellulose; β-glucosidases, which hydrolyze glucosides; amidohydrolase, proteases, and urease, involved in N mineralization; and phosphatases that remove phosphate groups from organic matter. Enzyme activities have often been used as indicators of microbial activity and can also be useful to interpret the intensity of microbial metabolism in wastes.

5.7 Physical and Biochemical Changes in Waste During Vermicomposting

Various studies have been conducted in the past to study the physicochemical changes in waste during vermicomposting, and the most commonly studied parameters include pH, organic carbon, NPK, enzymes, and heavy metals. A brief review of these parameters is given next.

5.7.1 pH

The pH of organic matter is an important factor for the survival and growth of earthworms and plays an important role in overall efficiency of the vermicomposting process. In the process, usually pH decreases from slightly alkaline to neutral or slightly acidic. There are different opinions related to the shift of pH toward neutrality. Pramanik et al. [36] reported that decomposition of organic matter leads to the formation of ammonium (NH_4^+) ions and humic acids. The presence of carboxylic and phenolic groups in humic acids causes lowering of the pH and ammonium ions increase the pH of the system. The combined effects of these two oppositely charged groups regulates the pH of vermicompost, leading to a shift of pH toward neutrality. In contrast, Ndegwa et al. [34] attributed the pH shift to the mineralization of nitrogen and phosphorus into nitrites or nitrates and orthophosphates as well as the formation of intermediate species in the organic matter decomposition. Lower pH in vermicomposts might be due to the production of CO_2 and other organic acids by microbial activity during decomposition of the organic matter [37]. Suthar [38] has reported that the shift in pH could be due to microbial decomposition during the process of vermicomposting.

5.7.2 Nitrogen Content

It is suggested that the final nitrogen content of vermicompost is dependent on the initial nitrogen content present in the organic waste and the extent of decomposition [39]. According to Viel et al. [40] losses in organic carbon due to substrate utilization by microbes and earthworms and their metabolic activities might be responsible for nitrogen addition. Decreases in pH may be another important factor in nitrogen retention, as nitrogen is lost as volatile ammonia at higher pH values. Addition of nitrogen in the form of mucus, nitrogenous excretory substances, body fluids, growth-stimulating hormones, and enzymes from earthworms has also been reported [41]. Kavian and Ghatneker [42] suggested the enhanced population of nitrogen fixers (*Azotobacter* and *Rhizobium*) in vermibeds, while working on vermicomposting of paper mill sludge.

5.7.3 Organic Carbon

Worms cause carbon loss by mineralization, which leads to decreases in total organic carbon during vermicomposting. The combined action of earthworms and microorganisms may be responsible for organic carbon loss from organic waste in the form of CO_2 [43]. Suthar [44] reported that earthworms promote microclimate conditions in the system that increase the loss of organic carbon from substrates to microbial respiration. Garg et al. [45] reported a 58.4% reduction in organic carbon in cow dung and 55.4% reduction in horse dung after 90 days of vermicomposting. Kaviraj and Sharma [46] reported a 20–45% loss of organic carbon during vermicomposting of municipality wastes. Earthworms and microorganisms use a large portion of carbon as a source of energy and nitrogen for building cell structure, bringing about the decomposition of organic matter [47].

5.7.4 Phosphorus Content

Phosphorus is an essential nutrient from a manurial point of view in vermicompost [48]. Satchell and Martin [49] found an increase of 25% in the phosphorus content of paper waste sludge after worm activity. The increase in phosphorus content was thought to be brought about directly by the actions of worm gut enzymes and indirectly by stimulation of the microflora. They also concluded that addition of phosphorus to vermicompost prevents nitrogen loss through ammonia volatilization. Ghosh et al. [50] reported that vermicomposting can be an efficient technology for the transformation of unavailable forms of phosphorus to easily available forms for plants. Vinotha et al. [51] also documented that microflora present in the feed material plays an important role in enhanced phosphorus in worm casts. According to Lee [52], if the organic materials pass through the gut of earthworms then some of phosphorus is converted to such forms that are available to plants. Suthar and Singh [53] attributed the release of available P content from organic waste to earthworm gut phosphatases and P-solubilizing microorganisms present in worm casts.

5.7.5 Potassium Content

Orozco et al. [54] reported that potassium content in vermicompost prepared from coffee pulp was lower than in the parent material, which may be due to its leaching by excess water that drained through the waste material. Delgado et al. [55] reported higher potassium content in vermicompost prepared from sewage sludge than in the parent material. Benitez et al. [56] reported that the leachate collected during the vermicomposting process had higher potassium concentration. Yadav et al. [57] also reported an increase in potassium in vermicompost after bioconversion of various materials. This increase was attributed to the reduction in the volume of the waste during vermicomposting. The potassium content in the vermicomposts prepared from various wastes is given in Table 5.2.

Table 5.2 Potassium Content in Waste Material and Vermicompost

Waste Material	Initial K Content in Waste Material (g/kg)	Final K Content in Vermicompost (g/kg)	References
Sugar mill Effluent treatment plant sludge (ETP) sludge (40%) + biogas plant slurry (60%)	13.8	12.3	[58]
Distillery sludge (40%) + cow dung (60%)	8.53	22.1	[38]
Paper mill sludge + cattle manure (1:4)	23	7.6	[59]
Solid textile mill sludge (30%) + cow dung (70%)	5.5	3.3	[60]
Beverage industry waste + cow dung (1:1)	29.2	17.6	[61]
Fly ash + cow dung (1:3)	11.8	18.8	[47]

5.7.6 C/N Ratio

The C/N ratio of the waste material is important for microbial activity. The ideal C/N ratio for vermicomposting is approximately 30:1. The C/N ratio of the waste material changes significantly during vermicomposting because of the loss of carbon as CO_2 and production of nitrogenous excrements by worms [62]. It is also an important indicator of the stabilization and maturity of waste materials [27]. Various studies on vermicomposting have reported a decrease in the C/N ratio of organic wastes, although the decrease is different for different organic wastes. The C/N ratio of vermicomposts prepared from various materials is given in Table 5.3. Aira et al. [63] reported that C/N ratio strongly affects the worm population structure in vermicomposting systems. In a low C/N ratio-containing feed the worm population was composed mainly of mature earthworms (60%), whereas in a high C/N ratio feed the worm population was mainly composed of juveniles and hatchlings (70%).

5.8 Vermicomposting of Urban Waste

Various organic wastes of different origins such as agriculture, industry, and domestic sectors, can be vermicomposted effectively provided they do not contain any toxic substance for the earthworms. Various vermicomposting studies using different organic wastes along with their results at the end of the process have been briefly represented in Table 5.4.

Table 5.3 C/N Ratio of Various Waste Materials and Vermicomposts

Waste Material	Initial C/N Ratio of Waste Material	Final C/N Ratio of Vermicompost	References
Cow dung	60.6	6.9	[64]
Water hyacinth (50%) + cow dung (50%)	47.2	8.4	[64]
Cow dung (70%) + poultry droppings (30%)	78.8	14.8	[65]
Biogas plant slurry	80.0	36.8	[66]
ETP sludge + cow dung mixed in various ratios	38.6–50.2	9.6–26.3	[24]

Table 5.4 Vermicomposting Studies of Various Organic Wastes

S. No.	Organic Waste	Organic Amendment/ Bulking Agent	Earthworm Species	Vermicomposting Duration	Results at the End of the Vermicomposting Process	References
1	Animal manure	Mushroom residues	*Eisenia fetida*	120 days	Reduction in C/N ratio and increases in N, P, K concentrations; humic acid content; humification ratio; and humification index were observed, in addition to a decrease in total heavy metal (i.e., As, Pb, Cu, Zn) concentrations.	[114]
2	PW	Anaerobically digested CDS	*E. fetida*	90 days	Three beds were set with various ratios of PW and CDS (100% CDS; 75% CDS + 25% PW; 50% CDS + 50% PW). There was a decrease in pH, TOC, C/N ratio, and C/P ratio, but increase in Ca, Na, and total NPK.	[115]
3	Sewage sludge and mushroom residue	Cattle dung	*E. fetida*	3 years in an integrated crop—vermiculture system	The crop—vermiculture system used no tillage or chemical fertilizer input, compared to conventional cultivation, and attained higher corn yield, improved soil porosity, and increased soil fertility. Although sewage sludge application had some cumulative effect on the heavy metal contents of soil, grain, and earthworms, short-term application was relatively safe.	[116]
4	Rabbit manure	—	*E. fetida*	200 days	Continuous-feeding reactors at optimal moisture of 66—76% were maintained. A pH decrease from 8.3 to 7.6 but no changes in EC were observed. A decrease in the levels of bacteria and fungi in layers occurred as the process progressed.	[75]
5	Cattle dung	-	*E. fetida*	90 days	The dissolved organic C was steady around 2.7 g/kg after 60 days and the dissolved organic C/N ratio decreased from 19.77 to 5.26. Decreases in the aliphatic, proteinaceous, and carbohydrate components and increases in the aromaticity and oxygen-containing functional groups in the water-extractable organic matter were observed.	[117]
6	Seven mammalian wastes (cow, buffalo, horse, donkey, sheep, goat, and camel)	—	*E. fetida*	105 days	The worm biomass gain was in the order sheep $>$ donkey $>$ buffalo $>$ goat $\approx$ cow $\approx$ horse $>$ camel. The number of cocoons produced per earthworm per day in the animal excreta was in the order sheep $>$ cow $\approx$ horse $\approx$ goat $>$ camel $>$ donkey $>$ buffalo. The cocoon production was several folds higher in sheep waste than in buffalo waste.	[118]

7	Sewage sludge	Rice straw	*E. fetida*	21 days	Lower pH and water-extractable organic carbon along with higher EC and nitrate was observed. Vermicomposting promoted the hydrolysis/transformation of macromolecular organic matters and the degradation of polysaccharide-like and protein-like materials.	[100]
8	Corn stalk residue	Sewage sludge	*E. fetida*	70 days	TOC, TVS, TKN, and C/N ratio decreased, whereas EC, TP, nitrate, and heavy metals increased. Increasing the concentration of sludge caused a decrease in the contents of TOC and TVS and in the C/N ratio and an increase in the content of TKN, nitrate, TP, and EC.	[101]
9	Rabbit manure	Sewage sludge or vinasse waste	*E. fetida*	56 days	Sewage sludge vermicomposts had higher humus, nutrient, and total metal contents, but lower soluble salts than vinasse vermicomposts. The number and mass of worms were higher in rabbit manure, followed by sewage sludge, at decreasing doses.	[102]
10	Sewage sludge	Cattle manure and saw dust	*E. fetida*	—	Decreased C/N ratio, higher loss in carbon, soluble BOD and soluble COD, and higher gain in TN and TP was observed.	[103]
11	Sewage sludge	Cow dung	*E. fetida*	60 days	The dissolved organic carbon, COD, and C/N ratio of the substrates decreased; the aromaticity of WEOM from the substrates was enhanced, and the amount of volatile fatty acids declined markedly. Fluorescence spectra indicated that vermicomposting caused the degradation of protein-like groups and the formation of fulvic and humic acid-like compounds in the WEOM of the substrates.	[104]
12	Temple waste, kitchen waste, and farmyard waste	Cow dung	*E. fetida*	120 days	The worm biomass was maximum in temple waste vermicompost compared to kitchen waste and farmyard waste vermicomposts. Temple waste vermicompost showed better results especially in terms of EC, C/N, C/P, and TK.	[68]
13	Kitchen waste	Cow dung	*E. fetida* and *Lampito mauritii*	150 days	Both species resulted in increased NPK and decreased C/N and C/P ratios. There was moderate mineralization and faster decomposition by *E. fetida* in comparison to moderate mineralization and moderate decomposition by *L. mauritii*. The cocoons and hatchling production by *E. fetida* was more than that by *L. mauritii.*	[41]
14	Leaf waste	—	*Eudrilus eugeniae*	25 days	The levels of both macro- and micronutrients in the vermicompost were significantly higher than initial raw waste.	[72]

Continued

Table 5.4 Vermicomposting Studies of Various Organic Wastes—cont'd

S. No.	Organic Waste	Organic Amendment/ Bulking Agent	Earthworm Species	Vermicomposting Duration	Results at the End of the Vermicomposting Process	References
15	Rice residues	Cow dung	*E. eugeniae*	60 days	Increases in Ca (11.4—34.2%), Mg (1.3—40.8%), P (1.2—57.3%), and K (1.1—345.6%) contents and a decrease in C/N ratio (26.8—80.0%), as well as increases in heavy metal content [iron (17—108%), copper (14—120%), and manganese (6—60%)] were seen.	[74]
16	Tomato crop waste and almond shells	—	*E. fetida* and *E. andrei*	261 days	Composting, vermicomposting, and integrating of both were done. • Particle size decreased during composting, yet it increased during vermicomposting and the combined process because of the amalgamation of small particles. • The pH was alkaline throughout the processes. • A decrease in EC and greater leaching of organic matter, TN, and most macronutrients in vermicomposting and the combined process were observed compared to composting.	[76]
17	RH	Market-refused fruit (B, H, or papaya)	*E. eugeniae*	63 days	Vermicomposting resulted in increased K (15.0—121.4%), P (2.4—49.5%), and Ca (6.9—99.0%). Among all the RH treatments, RH that was mixed with market-refused papaya (1:1) showed better quality vermicompost with higher nutritional status.	[77]
18	EFB	POME sludge	*E. fetida* and *E. eugeniae*	84 days	Maximum worm biomass and maximum cocoons were recorded for *E. fetida* in 70% EFB + 30% POME feed mixture. The results indicated that the addition of 30%, 40%, and 50% POME sludge to the EFB is suitable for vermicomposting, suggesting that *E. fetida* may be a better choice than *E. eugeniae* for the rapid propagation of earthworms in palm oil wastes.	[73]
19	Cow dung, grass, aquatic weeds, and municipal solid waste	Lime and microbial inoculants	—	—	Cow dung was the best substrate for vermicomposting. The application of lime (5 g/kg) and inoculation of microorganisms increased the nutrient content in vermicompost and also phosphatase and urease activities. *Bacillus polymyxa*, the free-living N fixer, increased N content of vermicompost significantly compared to other inoculants.	[36]

B, banana; *CDS*, cattle dung slurry; *EC*, electrical conductivity; *EFB*, empty fruit bunch; *H*, honeydew; *POME*, palm oil mill effluent; *PW*, poultry waste; *RH*, rice husk; *TK*, total potassium; *TKN*, total Kjeldahl nitrogen; *TN*, total nitrogen; *TOC*, total organic carbon; *TP*, total phosphorus; *TVS*, total volatile solids; *WEOM*, water-extractable organic matter.

It is estimated that about 40% of municipal solid waste is organic in nature in most developing countries. This fraction of waste can be gainfully vermicomposted at the household or municipality level in a centralized manner. Home composting and vermicomposting have been reported for the treatment of the organic municipal solid waste over an 8-month period to determine the quality of the compost produced [67]. The vermibins had a treatment capacity of 50 g biowaste per liter, whereas in the home composter it was 16 g biowaste per liter. The home composter required the addition of 6.3 g of bulking agent per liter of composter. The quality of the final products, compost and vermicompost, was similar in both cases, with each batch of compost having a low metal content and a high degree of stability, with dynamic respiration indexes of 0.43 and 0.89 mg O_2/g organic matter per hour for compost and vermicompost, respectively. Gaseous emissions from the vermicomposters were lower than from the home composters. No odors were detected from either system. The study concluded that home composting and vermicomposting can be considered suitable alternatives to divert a portion of the biowaste from the traditional waste-management system.

In another study, Nair et al. [69] investigated the combination of thermocomposting and vermicomposting to improve the efficiency of waste decomposition and assess the optimum period required in each method to produce good quality compost. They concluded that thermocomposting prior to vermicomposting helped in waste stabilization, pH and moisture stabilization, mass reduction, and pathogen inactivation. The study revealed that for treating kitchen waste, thermocomposting for 9 days followed by 2.5 months of vermicomposting produced pathogen-free compost.

Agricultural and agro-industrial residues, if managed properly using composting and vermicomposting, can be beneficial to agriculture, because these contain important plant nutrients such as NPK. In general, a great proportion of the crop nutrient input during cultivation returns in the form of plant residues. It is estimated that 30–35% of applied N and P and 70–80% of K remains in the residues of food crops. Such nutrient-rich crop residues are better options as feed for earthworms in vermicomposting [70,78]. Hanc and Chadimova [71] reported the vermicomposting of apple pomace waste mixed with straw and the process was evaluated on the basis of agrochemical properties of vermicompost and worm biomass. The vermicompost was slightly acidic to neutral pH (5.9–6.9) and had optimal electrical conductivity (EC) (1.6–4.4 mS/cm) and C/N ratios (13–14). The total nutrient content increased during vermicomposting for all of the treatments with the following average final values: N 2.8%, P 0.85%, K 2.3%, and Mg 0.38%. Gómez-Brandón et al. [75] investigated the vermicomposting of tomato-plant waste (TP) using paper mill sludge (S) as complementary waste. Earthworm development in TP, S, and two mixtures of both wastes was monitored for 24 weeks and compared with that in cow dung (D). The results showed that earthworms cannot survive in TP alone, but a mixture of TP with S at a ratio of 2:1 or 1:1 supported earthworm development equivalent to that observed in D. The efficiency of the process was assessed by analyzing the phospholipid fatty acid composition, chemical features, plant-nutrient content, metal concentration, enzyme activities, and germination index (GI). A commercial vermicompost was also analyzed and taken as a reference of vermicompost quality. Phospholipid fatty acid analysis revealed that earthworm activity strongly transformed initial microbiota inhabiting the waste, giving rise to vermicompost microbial communities that were similar to those of a commercial vermicompost. Both mixtures of TP and S were stabilized, as indicated by decreases in their C/N ratio and enzyme activities together with increases in their degree of maturity (GI ~ 100%) after the process. This study demonstrated that the vermicomposting of TP together with S allows the recycling of both wastes.

A number of other agricultural and agro-based industrial wastes used in vermicomposting are given in Table 5.5.

A large number of weeds that grow at an alarming rate and spread very fast in cultivated lands, pastures, grasslands, forests, and aquatic systems are also a good source of organic matter. Various studies have revealed the decomposition of various weeds into vermicompost, thus eradicating the problems associated with them. Rajiv et al. [91] reported the production of parthenin toxin-free vermicompost from *Parthenium hysterophorus* L. amended with cow dung using *E. eugeniae*. Thirty to thirty-five percent of organic carbon and 32–48% of phenol contents were reduced during the process after 45 days of earthworm activity. Fourier transform infrared spectra revealed the absence of parthenin toxin and phenols in vermicompost obtained from high concentrations of cow dung. Water hyacinth (WH) (*Eichhornia crassipes*) is a noxious weed all over the world because of its high growth rates. Several authors have reported the vermicomposting of WH using various species of earthworms [64,95,96]. These researchers have shown that vermicomposting is among the promising alternatives for the management of this weed but the final product may have higher concentrations of heavy metals due to the higher heavy metal bioaccumulation potential of WH [97]. Chemical speciation of heavy metals during composting is a useful technique for determining the chemical forms in which these metals are present [98]. Pare et al. [99] reported that water-soluble and exchangeable fractions of metals are most available to the plants. Singh and Kalamdhad [92] examined the speciation of heavy metals during vermicomposting of WH with cattle manure and sawdust by using *E. fetida* for 45 days in accordance with the Tessier sequential extraction method. The exchangeable fraction of Mn and Zn was converted into less mobile fractions such as reducible, oxidizable, and residual in the vermicompost. The residual fraction of Zn, Ni, Pb, Cd, and Cr was dominant from initial to final compost. The exchangeable and carbonate fractions of Cu, Ni, and Cr were reduced. The authors concluded that *E. fetida* was incredibly effective for reduction of the bioavailability of heavy metals during the vermicomposting of WH mixed with cattle manure and sawdust.

Najar and Khan [94] studied the potential of *E. fetida* to recycle various types of freshwater weeds (macrophytes) used as substrates in various reactors (*Azolla pinnata* reactor, *Trapa natans* reactor, *Ceratophyllum demersum* reactor, free-floating macrophytes mixture reactor, and submerged macrophytes mixture reactor) during a 2-month experiment. The reactors showed increased pH, EC, N, and K, but decreased organic carbon and C/N ratio. Hierarchical cluster analysis grouped five substrates (weeds) into three clusters: poor vermicompost substrate, moderate vermicompost substrate, and excellent vermicompost substrate.

Table 5.5 Various Agricultural and Agro-industrial Wastes Tested for Vermicomposting

S. No.	Agricultural and Agro-Industrial Waste	Organic Amendment/Bulking Agent	Earthworm Species	Pretreatment (Duration)	Vermicomposting Duration	References
1	Java citronella waste (*Cymbopogon winterianus* Jowitt)	Cow dung	*Perionyx excavatus*	15 days	105 days	[79]
2	Postharvest residues of wheat, millets, *Sorghum vulgare*, and a pulse, *Vigna radiata*	Animal dung	*Eudrilus eugeniae*	21 days	150 days	[38]
3	Fresh banana leaves	Cow dung	*E. eugeniae*, *Eisenia fetida*, *Perionyx sansibaricus*, *Pontoscolex corethrurus*, and *Megascolex chinensis*	15 days	—	[80]
4	Guar gum industry waste	Cow dung and sawdust	*P. excavatus*	20 days	150 days	[44]
5	Winery waste	Manure	*Eisenia andrei*	—	16 weeks	[81]
6	Sago industry solid waste	Cow dung and poultry manure	*E. fetida*	21 days	45 days	[82]
7	Press mud	Bagasse and sugarcane trash	*Drawida willsi*	30 days	40 days	[83]
8	Industrially produced wood chips	Sewage sludge	*E. fetida*	28 days	94 days	[84]
9	Sugar mill filter cake	Cow dung	*E. fetida*			[85]
10	Sugar industry sludge	Cow dung, biogas slurry, and wheat straw	*E. fetida*	15 days	90 days	[86]
11	Beverage industry sludge	Cattle dung	*E. fetida*	15 days	120 days	[61,87]
12	Spent mushroom waste	Cow dung	*E. fetida*			[88]
13	Dairy sludge	Cereal straw and wood shavings	*E. andrei*		60 days	[89]
14	Distillery industry sludge	Cow dung	*P. excavatus*	15 days	90 days	[53]
15	Olive oil industry waste	Sheep manure	*E. fetida*	—	9 months	[90]
16	Food industry sludge	Cow dung and poultry droppings	*E. fetida*	28 days	91 days	[57]
17	Food industry sludge	Cow dung	*E. fetida*	21 days	84 days	[24]
18	*Parthenium hysterophorus* weed	Cow dung	*E. eugeniae*	60 days	45 days	[91]
19	Water hyacinth	Cow dung	*E. fetida*	21 days	147 days	[64]
21	Water hyacinth	Cattle manure and sawdust	*E. fetida*	—	45 days	[92]
22	*Lantana camara* leaf litter	Cow dung	*E. fetida*	21 days	60 days	[93]
23	Water weeds (macrophytes)		*E. fetida*	—	60 days	[94]

Sewage sludge is an unavoidable waste of wastewater treatment processes. Being rich in micro- and macronutrients, it can be a potential feedstock in vermicomposting. Various studies conducted on vermicomposting of sewage sludge have been encapsulated in Table 5.4. On-site sanitation solutions have gained much interest in recent years. Commonly available on-site sanitation systems are composting latrines and urine-diverting dry toilets. Numerous reports demonstrate the capacity of vermicomposting systems to inactivate Enterobacteriaceae, such as *Salmonella* spp., *Escherichia coli*, and *Shigella* spp. [105–107]. However, opinions differ as to whether vermicomposting has the ability to destroy or inactivate parasites such as the intestinal worm *Ascaris* spp. [108–110], whereas little is known about its effect on viruses.

Lalander et al. [111] investigated the hygienic quality of composted materials treated in six UDVTs (urine-diverting vermicomposting toilets; containing mainly solid feces and toilet paper) employing *E. fetida* that had been in operation from 2 to 5 years in France. The concentrations of *Salmonella* spp., *Enterococcus* spp., thermotolerant coliforms, and naturally occurring coliphages (used as indicators for animal viruses), as well as physicochemical parameters, were analyzed. The study demonstrated that UDVT systems are a viable option for on-site management of human waste, as the vermicomposted material was odor free and homogenized. Buzie-Fru [112] developed and tested a continuous single-chamber vermicomposting toilet. He found that optimal conditions for vermicomposting of feces were a moisture content of 65–80% at 20–25°C, achieving 50–80% reduction in organic carbon after 96 days of treatment.

Hill and Baldwin [113] worked on the performance of composting toilets. They reported that source-separating vermicomposting toilets (SSVCs) outperformed mixed-latrine microbial composting toilets (MLMCs). MLMCs incurred 10 times greater operational costs, created 10 times more operator exposure, and employed no proven pathogen reduction mechanism. In contract, SSVCs had low maintenance costs and risks, adequate worm density for pathogen destruction, and reduced *E. coli* in neutral, stable, and mature end products.

Li et al. [119] reported vermifiltration as a new technology to process organically polluted water. A pilot plant associated with a swine facility (piggery) with 66 swine was developed to treat diluted manure, produce earthworms and vermicompost, and reduce air pollution. The earthworm population was increased by 30% in 4 weeks, indicating the acclimation of the earthworms. An ≈50% reduction in ammonia emissions was observed for the whole system. Higher water (+100%), carbon (+70%), and total nitrogen (+80%) gaseous losses were observed compared to conventional breeding on a slatted floor. The results indicated that vermifiltration can be a future technology in environment protection.

5.9 Vermicompost: Importance

Vermicompost is known as a sustainable source of micro- and macronutrients and works as excellent organic manure at least five to seven times more nutritive than all other composts and gives 30–40% higher crop yields over chemical fertilizers. It has been reported that vermicompost contains plant growth hormones, suppressive microbes, and enzymes [120,121], which not only enhance microbial populations but also hold nutrients for longer periods [1]. Vermicompost also consists of plant-growth regulators, such as auxins, gibberellins, and cytokinins [122], and humic acids [123], which are responsible for increased plant growth and yield. These plant-growth regulators are produced by actions of microbes involving fungi, bacteria, and actinomycetes [31]. The physical properties like high porosity, aeration, drainage, water-holding capacity, and microbial activity in vermicompost provide an excellent home environment for microbial activities and for strong retention of nutrients [124]. Because of these beneficial properties vermicompost can be directly applied to soil to increase soil organic matter content and nutrients that improve soil structure and increase cation-exchange capacity.

Another economic and environmental significance of vermicompost usage is that its production is about 75% cheaper than that of chemical fertilizers. Moreover, with the use of vermicompost over the years, the natural fertility of soil is maintained and its physical, chemical, and biological properties are improved, whereas the prolonged use of chemical fertilizers makes the soil devoid of fertility.

5.10 Effects of Vermicompost on Crops

Various forms of vermicompost are reported to have beneficial effects on a number of crops in both pot and field studies. The beneficial effects may include stimulation of seed germination [125–127], increased growth [128], protection against pathogens [129,130], increasing overall crop productivity [131–133], etc. However, results are variable, which may be due to the plant responses to vermicompost. Table 5.6 encapsulates some studies conducted with the use of vermicompost obtained from various waste materials in potting mixtures and their effects on growth and yield of various crops/plants.

The effects of vermicompost (prepared from an allelopathic *Lantana camara*) on cluster bean (*Cyamopsis tetragonoloba*) were studied [144]. In test plots, the soil was treated with the vermicomposts at 5, 7.5, and 10 tonnes/ha. The results indicated 51.5% more germination in the vermicompost treatments compared to controls. In addition, vermicompost application enhanced root nodule formation and reduced disease incidence.

Belda et al. [145] conducted the experiments to compare the suitability of compost and vermicomposts (prepared from the same batch of tomato crop waste) as growth media for the production of two ornamental plants (*Calendula officinalis* and *Viola cornuta*). Each material was mixed with *Sphagnum* peat at 100:0, 75:25, 50:50, 25:75, and 0:100 (peat control) proportions by volume. The compost was phytotoxic as indicated by reduction of seed germination, chlorophyll content, and plant growth of both plants. Vermicompost did not affect seed germination but reduced plant growth, though significantly less than compost. Mixing these materials with peat improved

Table 5.6 Usage of Vermicompost Produced From Various Waste Materials in Crop Production

S. No.	Waste Taken for Vermicompost	Plant/Crop Grown	Vermicompost Application Rate	Duration of Experiment	Effects	References
1	Cattle manure, food waste, and paper waste	Petunia	10–100%	79 days	Enhanced germination of petunias, increased dry shoot and root weights and numbers of flowers were observed.	[134]
2	Wastewater sludge and cow manure	Bean (*Phaseolus vulgaris* L.)		117 days	Growth and yield of bean plants was improved by use of vermicompost compared to those grown with inorganic fertilizer.	[135]
3	Pig manure	Tomato, marigold, pepper, and cornflower	20% v/v	28 days	40% increase in growth was observed in dry shoot tissue and leaf area of marigold, tomato, pepper, and cornflower.	[136]
4	Sheep manure	Maize (*Zea mays*)	5–10% v/v	35 days	Weight of maize plants grown in peat moss amended with vermicompost was increased.	[137]
5	Vegetable waste	Sunflower	3:1 (w/w)	10 weeks	Use of vermicompost enhanced uptake of nutrients (Na, Mg, Fe, Zn, Mn, Cu) giving high yield of biomass and overall growth of the sunflower plant.	[138]
6	Cow manure	Chinese cabbage	0:7, 1:7, 2:7, 4:7, 7:0 (w/w)	30 days	Application of vermicompost significantly increased marketable yield, important nutrient metabolites, and antioxidant capacity of Chinese cabbage.	[139]
7	Banana peel	*Solanum lycopersicum*			High growth parameters, namely root and shoot length and number of leaves, were observed with vermicompost.	[140]
8	Food waste	Tomato and cucumber	20–40% v/v	6 weeks	Both 20% and 40% vermicompost substitution rates decreased damage by cucumber beetles to cucumber foliage and by hornworms to tomato foliage significantly.	[141]

9	Food wastes	Peppers (*Capsicum annum*)	0%, 10%, 20%, 40%, 60%, 80%, and 100%	107 days	Peppers grown in 40% vermicompost and 60% Metro-Mix 360 (MM360) yielded 45% more fruit weight and had 17% greater mean number of fruits than those grown in MM360 only. The mean heights and numbers of buds and flowers of peppers grown in 10–80% vermicompost, although greater, did not differ significantly from those of peppers grown in MM360.	[142]
10	Food waste	Tomato, pepper, or cabbage	20–40% v/v		Vermicompost could have provided some essential nutrient elements, and these could either have increased the plants' resistance to pests or made the plants less palatable to the pests.	[143]
11	Pig manure	Marigold (*Tagetes patula*)	10–100% v/v	121 days	The greatest vegetative growth resulted from substitution of Metro-Mix 360 with 30% and 40% pig manure vermicompost, and the lowest growth was recorded in potting mixtures containing 90% and 100% vermicompost.	[123]

germination and growth. The diluted materials (compost at the 25:75 and vermicompost at the 50:50 and 25:75 proportions) produced good quality plants.

Vermicomposting of neem (*Azadiracta indica*) and its effect on growth and yield of brinjal (eggplant; *Solanum melongena*) has been reported [146]. The plants supplemented with vermicompost had better height, longer root length, and quicker onset of flowering and enhancement of fruit yield.

Effects of vermicompost on growth and marketable fruits of field-grown tomatoes, peppers, and strawberries have been studied [147]. In this study inorganic control plots were treated with recommended rates of fertilizers only and all of the vermicompost-treated plots were supplemented with amounts of inorganic fertilizers to equalize the initial N levels available to plants in all plots at transplanting. The results showed that tomato yields in all vermicompost-treated plots were consistently higher than those of the inorganic fertilizer-treated plots. Similar results were obtained for peppers and strawberries. The improvements in plant growth and increases in fruit yields may be due to increases in soil microbial biomass after vermicompost applications, leading to production of hormones in the vermicomposts acting as plant-growth regulators independent of nutrient supply.

In an another study commercially processed vermicompost, produced from food waste, paper waste, and cattle manure, was evaluated for its effects on the growth and yields of peppers (*Capsicum annuum*) [142]. The vermicompost application increased the growth and yields of peppers significantly, including increased leaf areas, plant shoot biomass, and marketable fruit weights and decreased yields of nonmarketable fruit. Increased growth and yield of peppers in the field were attributed to a number of positive effects of application of vermicompost in field soils. These increases could make a major contribution to the increased production of plant growth regulators such as humic acids and plant growth hormones adsorbed onto humic acids, which may have contributed to increased growth and yields of peppers in the field.

5.11 Conclusions and Perspectives

Earthworms are helpful in organic waste recycling and transform it into a valuable product, i.e., vermicompost. A variety of organic waste, viz., municipal, agricultural, industrial, sewage, and cattle waste, can be processed by vermicomposting systems. Vermicompost so produced has excellent physicochemical properties compared to traditional compost. Vermicompost produced from waste could be applied to crops as a source of plant nutrients. Extensive work has been done on vermicomposting so as to stimulate interest in the process and to appreciate its benefits. Still there are certain gaps in vermicomposting studies and research. Most of the studies have been conducted under controlled conditions at laboratory scale. So, pilot-scale or field-scale studies are further required for commercial exploitation of organic waste as substrate in vermicomposting. In addition to this, in most of the studies, exotic worm species have been employed for vermicomposting. Efforts should be made to use local earthworm species to avoid any adverse effects on worm diversity in the future.

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