Waste Biomass Valor (2018) 9:1073–1086
DOI 10.1007/s12649-017-9899-8

REVIEW

Earthworms as Organic Waste Managers and Biofertilizer Producers

Sartaj Ahmad Bhat[1] · **Jaswinder Singh**[2] · **Adarsh Pal Vig**[1]

Received: 26 July 2016 / Accepted: 13 March 2017 / Published online: 21 March 2017

Abstract Vermicomposting is the processing of organic materials by earthworms into homogeneous and humus-like material known as vermicompost. It is a complex mixture of fecal matter of earthworms and microorganisms. In vermicomposting system, earthworms act as voracious feeder, modifying composition of organic waste, gradually reducing its organic carbon and C:N ratio and retains more nutrients (nitrogen, potassium, phosphorus, calcium). The nutrient content is generally higher in vermicompost than in the traditional compost. Earthworm increases the surface area of any material and makes it more favorable for the activity of microbiota for further decomposition. Earthworms have the ability to consume various types of organic wastes such as livestock excreta, cattle dung, oil palm waste, agricultural residue, sewage sludge and other agro-industrial refuse. Studies suggested that organic wastes can be managed by the use of different species of earthworms and the production of vermicompost as a powerful biofertilizer in sustainable agriculture discouraging the use of chemical fertilizers. Vermicomposting accelerates the bioconversion process by two to five times as compared to traditional composting, thereby hastens the conversion of wastes into valuable biofertilizer. In the present review, earthworms are described as waste managers in utilizing and changing the physico-chemical properties of the organic wastes and highlight the need for the use of vermicomposting in organic waste recycling. Earthworm-microbe interaction and the nutrient status of final vermicompost are also discussed in detail.

Keywords Vermicomposting · Organic waste · Nutrients · Microbes · Sustainable development

✉ Adarsh Pal Vig
dr.adarshpalvig@gmail.com

1 Department of Botanical and Environmental Sciences, Guru Nanak Dev University, Amritsar, Punjab 143005, India

2 P.G. Department of Zoology, Khalsa College, Amritsar, Punjab, India

Introduction

Organic waste management is a global problem due to large scale urbanization, economic growth, and population explosion. Environmentally unhealthy disposal of organic wastes can degrade the environment and may cause diseases. Land filling, open dumping, and burning disposal practices are ecologically unsustainable, due to the production of certain toxic gases and leaching which can cause environmental pollution. The management of organic waste is a serious issue for the maintenance of pollution free environment. Globally, each year 3.4–4 billion tons of industrial and municipal waste is generated, of which non-hazardous industrial waste is about 1.2 billion tons [1]. About 960 million tons of solid waste is produced each year in India, of which 290 million tons are of industrial waste [2]. In India open dumping (94%) are the predominant mode of solid waste disposal and only 5% is used for composting [3]. Waste recycling or composting and its use for agricultural purposes is the best method for waste disposal [4]. The conversion of industrial waste into vermicompost is of double interest as along with checking pollution it also converts waste into a fertilizing material [5]. The production of earthworms in organic material is called vermiculture and the bioconversion of organic materials by earthworms is known as vermicomposting/earthworm technology. Vermicompost is one of the highest-grade and most nutrient-rich natural organic fertilizers in the world. Vermicompost contains highly enriched nutrients (nitrogen, potassium, phosphorus, calcium) which gradually make them easily available to plants [6]. Application of vermicompost in sustainable agriculture is thus a well-established choice to chemical fertilizers.

In the present review article, growth and reproduction of earthworms in organic wastes is discussed. Along with this, the paper discusses the earthworm-microbe interaction for stabilization/decomposition of wastes and also the quality of final vermicompost (nutrient status) as compared to composting without earthworms. There are number of research studies on the use of the vermicomposting process for the bioconversion of different organic wastes to produce organic fertilizer (vermicompost) at small scale (lab conditions). Waste management is not possible without earthworms. Practical utilization of earthworms as waste managers in towns, corporations at commercial level/large scale should be taken into consideration. The earthworm technology should be considered for employment of youth as this technology is cost effective and produces two productive outputs (biomass and compost) in stipulated duration.

Earthworm-Microbe Interaction

Earthworms are also called as the 'farmer's friend' or 'nature's ploughman'. Sir Charles Darwin described earthworms as the 'unheralded soldiers of mankind', Sir Anatoly Igonin called 'protector and producer' and Aristotle called them as the 'intestine of earth' as they maintain the fertility of the soil and also could digest varieties of organic substrates [7]. More than 4000 species of earthworms are reported in the world and in the India 420 valid species/subspecies belonging to 70 genera are known [8]. India contributes about 10.5 per cent of the world's earthworm diversity alone [8]. Earthworms are hermaphrodites with bilaterally symmetrical, segmented invertebrates grouped under phylum *Annelida* and class *Oligochaeta* with a dark brown body and clitellum for producing cocoons. Earthworms have a gizzard which crushes the organic materials to a smaller size. The gut of the earthworm is inhabited by microbial symbionts (bacteria, protozoa, and fungi) which is responsible for the organic matter degradation [9]. The different types of microflora present in different species of earthworms are listed in Table 1.

Based on feeding habitat, earthworm species have been classified into three types: epigeic, anecic and endogeic worms (Table 2) [19].

Out of these three types of earthworms, epigeic species shows good potential for vermicomposting. The important earthworm species for vermicomposting is *Eisenia fetida* as it has a high capacity of all environmental conditions, higher rates of decomposition of organic substances and high reproductive rate and short life cycle. Earthworm-microbe interaction is found to be complex. Microbes provide food for earthworms and the protozoa and fungi are of major importance in diet. Worms and microbes work together to increase the organic waste decomposition [20]. Vermicompost has higher microbial population than compost [21]. A large number of bacteria have been reported in vermicomposts produced by different earthworm species like proteobacteria, bacteroidetes, actinobacteria in *E. fetida* [10]. *Azotobacter*, autotrophic *Nitrosomonas, nitrobacter* in *Eudrilus* species [16]. *Pseudomonas oxalaticus* in *Pheretima* species [17]. *Bradyrhizobium japonicum* in *Lumbricus terrestris* [13]. Ismail [22] reported that earthworms have collaboration with free living soil bacteria and forms the drilosphere. The ingested material while passing through the gut of earthworms, increases the number of microbes up to 1000 fold [23]. The gut of earthworms contain the 'nitrogen-fixing' and 'decomposer microbes' which are released along with nutrients in their final excreta [15]

Table 1 List of different types of microflora present in different species of earthworms

Earthworm species	Microorganisms	References
Eisenia fetida	Actinobacteria, Bacteroidetes, Firmicutes, Proteibacteria, Verrucomicrobia *Bacillus* spp. *B. megaterium, B. pumillus, B. subtilis*	[10, 11]
Lumbricus terrestris	Florescent pseudomonas Filamentous actinomycetes *Bradyrhizobium japonicum*	[12, 13]
L. rubellus	*Rhizobium japonicum* *Pseudomonas putida* Acidobacteria, Firmicutes, β-proteobacteria	[14, 15]
Eudrilus sp.	*Azospirillum, Azotobacter*, Autotrophic *Nitrosomonas, Nitrobacter, Ammonifying* bacteria Phosphate solubilizers Fluorescent pseudomonas	[16]
Pheretima sp.	*Pseudomonas oxalaticus*	[17]
Aporrectodea trapezoides	*Pseudomonas corrugata* 214OR	[18]

Table 2 Classification and characteristics of different earthworm species

Characteristics	Epigeic species	Anecic species	Endogeic species
Habitat	3–10 cm, surface dwellers	30–90 cm, deep burrowing	10–30 cm, upper layer soil
Body size	Small	Large	Moderate
Color	Uniform body colouration	Pigmentation only at the anterior and posterior end	Weak pigmentation
Life cycle	Short	Long	Medium
Temperature tolerance	Tolerate a wide range of temperature	Poor temperature tolerance	Poor temperature tolerance
Live in	Near the surface litter or dung	Deep soil	Below the surface
Reproduction rate	High	Moderate	Low
Feeding habitat	Plant litter or mammalian dung, undecomposed litter	Decomposed litter, surface litter	Organic rich soil, subsurface soil material
Major role	Efficient bio-degraders and are good for vermicomposting	Distribution and decomposition of organic matter in soil	Soil mixing and aeration processes
Vermicomposting potential	Good	Low	Low
Common species	*Eisenia fetida, E. andrei, Eudrilus eugenie, Lumbricus rubellus, L. festivus, L. castaneus, Bimastus eiseni, B. minusculus, Drawida modesta, Dendrodrilus rubidus, Dendrobaena veneta* and *Perionyx excavatus*	*Lumbricus terrestris, L. polyphemus, Lampito mauritii, Apporrectodea trapezoids* and *A. longac*	*Octochaetona thurstoni, Aporrectodea caliginosa, Allolobophora rosea, A. caliginosa, Metaphire posthuma, Pontoscolex corethrurus, Drawida barwelli* and *Amynthas* species

and are beneficial to the soil health [24]. Final earthworm casts contains higher activities of protease, phosphatase, peroxidase, dehydrogenase, amylase and cellulose [25] and provides some biological benefits to soil [26]. Several researchers [27, 28] have reported that the microbiota of earthworm gut and cast can digest organic substances and polysaccharides. Earthworms and their microflora increases nitrogen mineralization that favours nitrification in the organic wastes [29]. Monson et al. [30] observed a maximum number of microbes in vermicomposted treated plots. A higher microbiota was also observed in paddy fields applied with vermicompost [31]. Chen et al. [32] observed that earthworms activated lignocelluloses degradation microorganisms (*Pseudomonas, Streptomyces, Pseudoxanthomonas, Mucor*, and *Cryptococcus*) there by speedup lignocelluloses decomposition in maize stover. Aira et al. [33] observed that *E. fetida* promoted fungal growth and fungal biomass depends on the density of worms. Koubova et al. [34] observed that the route of consumed organic substance through the gut of *E. fetida* and *E. andrei* increased the biomass of microbes and changed the microbial structure. Vivas et al. [24] observed that microbial diversity of olive waste was enhanced by *E. fetida* and the final vermicompost was detected by greater bacterial population. Microbiological investigations revealed that the earthworms and their microbiota have strong interactions with each other [35]. The population of microbes is enhanced in earthworm gut and finally in the vermicasts. The earthworm-microbe interaction is interdependent and the relationship can play a great role in producing high quality manure.

Growth and Reproduction of Earthworms in Organic Wastes

It is understood that earthworm species increases the rate of decomposition during vermistabilization of organic wastes [33]. Earthworm species have the ability to consume various types of organic wastes such as livestock excreta, cattle dung, oil palm waste, agricultural residue, sewage sludge and other agro-industrial refuse. Earthworms are hermaphrodites and at maturity develops ring shaped clitellum which secret a thick mucus to form a cocoon [36]. In earthworms production of cocoons starts at the age of 6 weeks till the end of 6 months. Quality and nature of organic material is one of the conditions determining the reproduction and growth of earthworms [37]. Yadav and Garg [38] reported increase in worm biomass at initial stages and later declined at final stages during vermicomposting of food industry sludge and water hyacinth using earthworm *E. fetida*. Availability of food at initial stages increases the worm biomass whereas exhaustion of food in the final stages decreases the earthworm biomass [39]. Many researchers have revealed that biochemical quality and the kind of food affects the earthworm biomass and reproduction [40–42]. In vermicomposting process, the decomposition and microbial density of organic wastes are important in determining the growth and reproduction of earthworms. Singh et al. [43] observed a continuous decrease of earthworm *E. fetida* in hundred per cent distillery sludge, but when it was mixed with cattle dung, earthworm biomass and reproduction was increased. Earthworm number and cocoons also decreased with increasing content of distillery sludge [44]. The decrease in earthworm number can be due to the toxic nature or unfavorable environment in feed substrate. Many researchers have reported that earthworm biomass grows faster at lower stocking densities [45–47]. For optimum stocking density 27–53 earthworms per kilogram per feed mixture is effective for vermicomposting process [47]. Many researchers have observed that the cocoon production was more in cow dung, whereas it was low in horse dung due to lower nutritional value [48]. Reinecke et al. [49] suggested that the ideal temperature for earthworm growth and production of cocoons is between 25 and 30 °C. Reinecke and Venter [50] suggested that in vermicomposting system the optimum moisture content for better growth and cocoon production should be maintained between 65–70%. Earthworm biomass and reproduction increases with decreasing carbon to nitrogen ratio in final feed mixtures. Organic wastes having more available forms of nutrients enhance earthworm growth and reproduction. Vermicomposting of different types of organic wastes are shown in Table 3.

Stabilization of Organic Wastes During Vermicomposting

Many researchers have studied biochemical changes in the organic waste during the process of vermicomposting. The comparison of nutrient content between the traditional compost and vermicompost are shown in Table 4. A brief review of physico-chemical parameters (pH, electrical conductivity, organic carbon, C:N ratio, nitrogen, phosphorus, potassium and heavy metals) is given below:

pH

The pH of organic wastes is an important factor affecting the vermicomposting process. Earthworms can remain alive in a pH range of 5–9 and the most desirable pH during the process of vermicomposting is recommended to be 7.5–8.0 [81]. pH is highly dependent on the initial raw material used for the stabilization process. In vermicomposting pH usually decreases from alkaline to neutral or acidic [40]. The shift in pH towards acidic or neutrality may be due to the formation of organic acids and mineralization of organic nitrogen and phosphorus. Many researchers have reported acidic nature of pH during vermicomposting of organic wastes [48, 82]. Garg et al. [83] have reported that in organic wastes at initial stages the nature of pH is alkaline (8.3–7.2), whereas during vermicomposting process, pH slightly shifts to neutral or acidic (6.3–7.1) conditions due to the intermediate products produced. Elvira et al. [84] concluded that the accumulation of organic acids and evolution of carbon dioxide in vermicomposting process lowers the pH of organic wastes as compared to initial feed mixtures. Vermicomposts of pH range 6–8.5 are capable for soil application [85]. In composting and vermicomposting process, increase in pH is mainly due to the utilization of organic acids and an increase in nutrient constituents of the organic wastes [86]. Datar et al. [87] observed increase in the pH of organic community solid waste using earthworm *Eudrilus eugeniae* and this increase may be due to the excess of organic nitrogen and later releases as ammonia, which gets dissolved in water and increases the pH of the final vermicompost [88]. Muthukamaravel et al. [89] also reported increase in pH, which may be attributed to the decomposition of nitrogenous materials. In vermicomposting process during initial stages, increase in pH value may be due to the formation of basic hydroxides and in final stages decrease in pH towards neutrality is due to the production of organic acids [90]. A number of reasons can be discussed for the change in pH during bioconversion of wastes by earthworms. The difference in pH among the different feed mixtures of organic wastes may be due to the quality of feed material which affected the mineralization process during vermicomposting.

Electrical Conductivity (EC)

EC reflects the salinity of an organic material. Phytoxicity may be caused by high salt concentrations therefore EC values of a vermicompost is a good indicator for agricultural purposes [91]. Lasaridi et al. [92] reported that the maximum tolerance limit of plants to EC is 4.0 $mScm^{-1}$ and a lower value than 4.0 $mScm^{-1}$ can be safely applied for agricultural purposes. Some researchers during vermicomposting process reported decrease in EC values [43, 74, 83] while as others report an increase in EC values [38, 66, 69, 75, 93, 94]. Karmegam and Daniel [95] observed an increase in the final EC values of vermicompost which may be due to the increase in soluble salt level, resulting from the action of worms and microbes. Kaviraj and Sharma [96] also reported an increase in final EC values during vermicomposting of municipal solid wastes and is due to the loss final weight of organic materials and release of mineral salts such as potassium, ammonium, phosphates etc in plant available forms. Kaur et al. [75] observed that in paper mill sludge vermicomposting, increase in sodium and potassium parameters and a decrease in total organic carbon content may be responsible for increased final EC values. Garg et al. [94] reported that increase in final EC values during vermicomposting process is mainly due to the free available minerals and ions produced during the breakdown and excretion by earthworms. Singh et al. [43, 74] observed a decline in final EC values during vermicomposting of beverage and distillery industry sludge. Decrease

Table 3 Vermicomposting of different types of organic wastes and growth features of different earthworm species

Organic waste	Amendment	Earthworm species	Vermicomposting period	Growth characteristics	References
Animal wastewater treatment plant sludge	Cow dung and swine manure	*Eisenia fetida*	60	The sludge amended with 40% swine manure was suitable medium for the growth of *E. fetida*, and with 40% cow dung was suitable medium for the fecundity of *E. fetida*	[51]
Jute mill waste	Cow dung and vegetable waste	*Metaphire posthuma*	80	The earthworm number, cocoons, body length and body weight was more in cow dung and vegetable waste mixed with jute mill waste in a 50:50 ratio and 50:30:20 ratio	[52]
Sewage sludge and wheat straw	Biochar	*E. fetida*	126	Sewage sludge and wheat straw amended with 4 and 8% of biochar increased the reproduction rate of *E. fetida*. Adding of biochar results in total earthworm biomass gain which was around 28%	[53]
Bakery industry sludge	Cow dung	*E. fetida*	105	Maximum earthworm biomass was observed in 90% cow dung + 10 Effluent treatment plant sludge of bakery industry	[54]
Biogas digestate	Wheat straw	*E. fetida*	150	Maximum growth and nutrients were achieved in 3:1 volume of biogas digestate and wheat straw	[55]
Compostable municipal waste solid	Cow dung	*E. fetida*	56	Maximum growth rate and reproduction was observed in 40–60% compostable municipal waste solid vermibeds	[56]
Sewage sludge	Cattle dung, pig manure	*E. fetida*	49	Maximum growth and reproduction was observed in cattle dung vermibeds than those with pig manure	[57]
Bagasse waste	Cattle dung	*E. fetida*	135	Maximum growth and reproduction was observed in 50:50 mixture of bagasse and cattle dung	[5]
Dewatered sludge (paper and pulp mill)	Saw dust	*E. fetida, Eudrilus eugeniae, Perionyx excavatus*	45	Best growth was observed with earthworm *E. fetida* in 70:30 mixture of dewatered sludge and saw dust, while the other two earthworm species worked almost similar in reactors	[58]
Pelletized dewatered sludge	–	*Bimastus parvus*	60	4.5 mm pelletized dewatered sludge supported more growth and reproduction of *B. parvus* than 14.5 mm pelletized sludge	[59]

Table 3 (continued)

Organic waste	Amendment	Earthworm species	Vermicomposting period	Growth characteristics	References
Sugar beet mud and pulp	Cattle dung	*E. fetida*	135	Best growth and fecundity were observed in 20:80 mixture of sugar beet mud and cattle dung whereas in sugar beet pulp and cattle dung highest growth and biomass was observed in 10:90 mixture	[60]
Waste carbide sludge	Vegetable waste, cow dung, saw dust	*E. fetida*	45	Higher earthworm biomass was observed in waste carbide sludge added reactors as compared to the control	[61]
Anerobic digestate	Cattle dung	*P. excavatus, P. sansibaricus*	60	Maximum number of earthworms, cocoons and hatchlings were observed in anaerobic digestate of *P. excavatus* followed by *P. sansibaricus*	[62]
Apple pomace	Wheat straw	*E. fetida*	30	Maximum growth was observed in lower mixtures of apple pomace but the addition of wheat straw did not enhance earthworm biomass	[63]
Distillery sludge	Cattle dung	*E. fetida*	150	Best growth was observed in 50:50 mixture of distillery sludge and cattle dung	[43]
Empty fruit bunches (oil palm industry)	Cow dung	*E. eugeniae*	84	Highest earthworm biomass was observed in two parts of empty fruit bunch and one part of cow dung	[64]
Leaf litters (silver oak and bamboo leaf litter waste)	Cow dung	*E. fetida*	70	*E. fetida* showed maximum growth rate and reproduction in all vermibeds of leaf litters	[65]
Pressmud	Cow dung	*E. fetida*	120	Best growth and fecundity of E. fetida was observed in 25:75 mixture of pressmud and cattle dung	[66]
Tea factory coal ash	Cow dung	*E. fetida, Lampito mauritii*	60	Highest growth of *E. fetida* was observed in 1:1 and 1:2 tea factory coal ash and cow dung mixtures, whereas growth of *L. mauritii* were comparatively lesser as compared to *E. fetida*	[67]
Dyeing sludge	Cattle dung	*E. fetida*	90	Maximum growth was observed in 25:75 mixtures of dyeing sludge and cattle dung	[68]
Fresh water weeds (macrophytes)	Cow dung	*E. fetida*	60	Maximum earthworm growth was observed in *Azolla pinnata* reactor and free-floating macrophytes mixture reactor	[69]
Sewage sludge	Spent mushroom compost	*Lumbricus rebellus*	105	Maximum growth was achieved in 20:80 mixture of sewage sludge and spent mushroom compost	[70]

Table 3 (continued)

Organic waste	Amendment	Earthworm species	Vermicomposting period	Growth characteristics	References
Temple floral offerings waste	Cow dung	*E. fetida*	120	Worm biomass was maximum in temple waste as compared to kitchen waste and farmyard waste	[71]
Milk processing industry sludge	Cow dung, sugarcane trash, wheat straw	*E. fetida*	90	Highest earthworm biomass was observed in 60% of milk processing industry sludge + 10% of cow dung + 30% of wheat straw	[72]
Tannery sludge	Cattle dung	*E. fetida*	120	The minimum mortality and highest population buildup of earthworms was observed in 100% cattle dung mixture followed by 25% of tannery sludge mixture (25:75 ratio)	[73]
Biosludge of beverage industry	Cattle dung	*E. fetida*	120	Best earthworm biomass was achieved with 7.5 g worm/kg 50:50 mixture of beverage industry sludge and cattle dung	[74]
Paper mill sludge	Cattle dung	*E. fetida*	150	Maximum growth was observed in 25:75 mixture of paper mill sludge and cattle dung	[75]
Thermal power plant flyash	Cattle dung	*E. fetida*	90	Minimum mortality and maximum growth of *E. fetida* was observed in 25:75 (FE25) mixture of flyash and cattle dung	[76]
Water lettuce biomass	Cow dung	*E. fetida*	28	The treatment setup with 60–80% of water lettuce showed the maximum growth and reproduction rate of *E. fetida*	[77]
Parthenium weed	Biogas plant slurry	*E. fetida*	60	Maximum biomass gain and cocoon production was observed in all vermibins, but the best growth were shown by 100% biogas plant slurry than the other combinations with parthenium weed	[78]
Food and vegetable processing waste	Buffalo dung	*E. fetida*	90	Best growth and reproduction of earthworm were observed in 100% buffalo dung feedstock. The results revealed that the suitability of food and vegetable processing waste (up to 50%) mixed with buffalo dung for increasing the population of earthworm and in providing potent organic manure for agronomic use	[79]
Cashew leaf litter	Animal dungs (cow dung, sheep dung and horse dung)	*P. excavatus*	60	The rate of growth (biomass), reproduction (cocoon production and hatchlings) of earthworm *P. excavatus* was maximum in 100% animal dung mixtures, followed by animal dung mixed with cashew leaf litter in 50:50 vermibeds	[80]

Table 4 Comparison of nutrient content of traditional compost and vermicompost (cattle dung)

Nutrient content	Traditional compost	Vermicompost
pH	8.40 ± 0.10	8.92 ± 0.09
Electrical conductivity (mS/cm)	3.22 ± 0.02	2.82 ± 0.09
Organic carbon (%)	45.40 ± 1.01	37.12 ± 0.11
C:N ratio	44.30 ± 1.62	15.46 ± 0.57
Nitrogen (%)	1.03 ± 0.24	2.40 ± 1.20
Phosphorus (%)	0.92 ± 0.30	1.49 ± 0.81
Potassium (%)	4.01 ± 1.20	1.90 ± 0.08
Sodium (%)	0.71 ± 0.20	1.41 ± 0.38

Source Bhat et al. [68]

in EC may be due to the stabilization of final mixtures and a decrease in ions after forming a complex.

Organic Carbon and Carbon to Nitrogen Ratio

Earthworms consume various organic wastes and decreases organic carbon during vermicomposting process. This reduction in organic carbon denotes the rate of degradation of organic wastes. The reduction in organic carbon in the final vermicompost is due to the loss of carbon from substrate through respiration by the combined action of earthworms and microbes [61, 76, 97]. In the vermicomposting process earthworms and microbes promote such conditions in the feed mixtures that it activates microbial respiration and degradation of organic wastes, thereby increases the loss of organic carbon [98]. Venkatesh and Eevera [99] reported that a major portion of carbon and nitrogen is used by microbes and earthworms for decomposition of organic wastes and may have decreased the large fractions of organic carbon as CO_2. Garg and Gupta [81] suggested that the reduction in organic carbon in initial stages of vermicomposting is more due to the availability of food at initial stages which increases the earthworm and microbial activity in the organic wastes. Ravindran et al. [100] reported the organic carbon decreased from 55.12 to 21.1% during vermicomposting of animal fleshing solid waste generated from leather industries. Earthworms thus bring about significant reduction in organic carbon content of the organic wastes and increase the waste bioconversion process.

Carbon to Nitrogen ratio (C:N ratio) reflect the waste decomposition and mineralization. Reduction in C:N ratio is due to maximum loss of carbon through microbial respiration in the form of CO_2 and increase in nitrogen in the form of mucus and stabilization of organic material by the earthworms [73, 93]. However in vermicomposting initial content of nitrogen in the feed mixtures are mainly responsible for the final content of nitrogen and the extent of decomposition. For faster organic waste stabilization, the optimum C:N ratio should be in between 25 and 30. Sinesi [101] suggested that a reduction in C:N ratio to <20 indicates organic waste stabilization and compost maturity which is an important tool for the growth of plants. Many researchers have reported that C:N ratio decreases sharply during vermicomposting and is one of the most widely used indicator for maturity of organic wastes [43, 44, 81, 102]. The loss of carbon and production of nitrogenous excreta increases the nitrogen content, which decreases the C:N ratio of feed mixtures.

Nitrogen

Nitrogen is easily available in vermicomposting technology as compared to other technologies for organic waste degradation. Many researchers have reported that the rearing of earthworms increases soil nitrogen which may be due to the death and decay of earthworms [103, 104]. Cynthia and Rajeshkumar [105] observed an increase in nitrogen content of final vermicompost mixtures of sugar industry and is due to the decomposition of waste by earthworms to increase the nitrogen bioconversion process. Earthworms increases the nitrogen content of final vermicompost through death of some earthworm tissues and microbial mediated nitrogen transformation results in further increase in nitrogen [106]. Tripathi and Bhardwaj [41] reported that during vermicomposting process addition of nitrogen content is due to the release of nitrogenous excretory substances, mucus, growth hormones and enzymes. Losses in organic carbon during decomposition of organic wastes should be responsible for enhancement of nitrogen [107]. Mineralization of carbon-rich materials and action of nitrogen-fixing bacteria during vermicomposting process increases mineral-N forms [108]. Ravindran et al. [100] reported that the nitrogen content of final vermicomposted animal fleshing waste increased from 0.81 to 1.34% from that of control. Yadav and Garg [109] suggested that mineralization of organic waste, decreases in pH, ammonium to nitrate conversion and decrease in organic carbon content should be responsible for addition of nitrogen in final vermicompost. While many researchers revealed that decrease in nitrogen content during the vermicomposting process. This may be due to ammonification, denitrification, NH_3 volatilization, leaching or due to release of ammonia [110, 111]. In general, increase in final nitrogen content of vermicompost depends upon the initial nitrogen content and the extent of mineralization.

Phosphorus

Phosphorus plays an important role in plant maturation. It is required for photosynthesis, root establishment, good flowering, energy transfer, fruit quality and fruit growth of various crops and plants. Hesse [112] reported that phosphorus in the form of orthophosphates ($H_2PO_4^-$ and $H_2PO_4^{2-}$) is taken up by plants. Phosphorus usually increases in the final vermicompost than initial wastes. Singh et al. [43] observed an increase of 13.83% in total phosphorus of distillery sludge after vermicomposting with *E. fetida* for 150 days. Hameeda et al. [113] reported that at different pH various types of microbes act on phosphorus for its solubilisation during composting and vermicomposting. In vermicomposting process, increase in phosphorus is mainly due to acid formation during organic waste decomposition by microbes and is responsible for solubilisation of insoluble phosphorus [114]. Earthworm increases the availability of phosphorus in the vermicomposting system. This release of phosphorus is performed by earthworm gut phosphatases and phosphate-solubilizing microbes present in the final feed mixtures of vermicompost [115]. Yadav and Garg [116] reported that vermicomposting process increases phosphorus content through decomposition and mineralization of phosphorus by phosphate and bacterial activity of worms. Microflora present in vermicompost feed mixtures plays an important role in increased content of phosphorus of final earthworm casts [117]. Bhat et al. [66] reported 22.60% increase in total phosphorus in the final vermicompost products of pressmud sludge. Kaur et al. [75] also reported that vermicomposting feed mixtures had higher phosphorus content as compared to the mixtures of composting without earthworms. Ravindran and Sekaran [118] revealed that the net loss of dry mass which concentrates the phosphorus in the final feed mixtures of vermicomposting process increases the phosphorus content. Yadav and Garg [38] also reported 30–60% increase in phosphorus content in the final products of vermicomposting than the initial raw waste.

Potassium

Potassium along with phosphorus and nitrogen plays an important role for plant growth. It is an essential nutrient used in cell division and root development by plants [109]. Many researchers have also reported that vermicomposting significantly increases the potassium concentrations in the final feed mixtures of organic wastes [5, 44]. Kaviraj and Sharma [96] suggested that the potassium is increased by the enhanced microflora present in earthworm gut. Increase in potassium concentration was also observed in the final vermicompost of distillery sludge [43]. Yadav and Garg [38] observed an increase in potassium content of industrial solid wastes and weeds. Increased potassium content in final feed mixtures ranged from 41.2 to 60% as compared to the initial raw waste mixtures. Some studies regarding potassium concentration in final vermicomposts are contradictory as potassium may release due to leaching of soluble elements by excess water of bottom [84, 119]. Singh et al. [43] suggested that the earthworm may use the available potassium, as potassium was more in feed mixtures without earthworms as compared to feed mixtures with earthworms. Leachates collected during vermicomposting of sewage sludge had higher content of potassium [110]. Bhat et al. [66, 68] have reported 15.78 and 66.7% decline in total potassium content in the final vermicompost feed mixtures of dyeing sludge and pressmud sludge respectively. Rise in pH during vermicomposting process may be responsible for decrease in potassium ions, as it is more susceptible to fixation by colloids at higher pH [120].

Heavy Metals

Heavy metals (Cd, Cr, Cu, Fe, Mn, Ni, Zn) are important trace elements for growth, metabolism and development of plants and animals. Heavy metals in excess concentrations have toxic effects [121]. Metal toxicity depends on metal concentration, mobility, bioavailability and metal uptake mechanism [122]. During vermicomposting process earthworms ingest organic materials and are therefore exposed to metals from the wastes and bio accumulates in their bodies [44]. Earthworms have the ability to accumulate heavy metals in polluted soils [123]. Intestinal microflora and chloragocyte cells of earthworms have the ability to detoxify the heavy metals [124]. So vermicomposting technique can be used for the removal of toxic pollutants and the breakdown of toxic wastes to nontoxic forms. Saxena et al. [123] revealed that during vermicomposting process, earthworms can accumulate metals at superior concentrations. Jain et al. [124] have successfully converted flyash into vermicompost. The results suggested that *E. fetida* accumulates heavy metals and also reduces Cr(VI) to Cr(III). The vermicomposting of flyash was an efficient technology for decreasing the metal concentrations in fly ash. Gupta et al. [125] also observed reduction in heavy metal content during vermicomposting of flyash. The study revealed that earthworm bodies retain heavy metals and decreases heavy metal content in the final vermicompost. Suthar and Singh [115] reported that vermicomposting of distillery sludge reduced total metal content than initial raw substrate. The authors suggested that reduction in metal content was higher in feed mixtures which show better decomposition and earthworm growth. Many researchers have reported that earthworms accumulate heavy metals and retained within worm bodies if reared for a longer duration in contaminated soils [126–128]. Comparative assessment of heavy metals during the composting and vermicomposting of municipal solid waste has been studied by Soobhany et al. [129]. The authors concluded that metal loss was more in vermicomposting due to earthworm activity in the waste mineralization than the composting process. Soobhany et al. [130] also observed heavy metal reduction (Cd, Cr, Cu, Co, Zn) during vermicomposting of organic wastes by *Eisenia eugeniae* in the final feed mixtures. Heavy metal concentration was increased in the tissues of earthworms from initial to final process (677.5–6791.4 mg/kg for Cd, 2345.4–2355.0 mg/kg for Cr, 1042.0–1060.55 mg/kg for Cu, 723.8–741.7 mg/kg for Co, 486.7–620.6 mg/kg for Zn, 35.4–68.6 mg/kg for Ni). Singh and Kaur [131] reported decrease in metal content in the final vermicompost mixtures of chemical sludge and spent carbon wastes generated from soft drink industries. Decline in heavy metal contents corresponded with an increase in earthworm weight. Cells of yellow tissue in earthworm body have an ability to accumulate heavy metals [132]. Gupta et al. [133] revealed that during vermicomposting of water hyacinth, decline in heavy metal content could be due to leaching or retained by earthworms. Ravindran et al. [134] reported that in final products of tannery solid waste, heavy metals were highly decreased by earthworms as compared to without earthworm feed mixtures. The highest reduction of heavy metals after 25 days of processing was in order of Cu 58.5%, Cr 55.8%, Zn 35.7%, Mn 23.4% and Fe 19%.

Some researchers reported increased heavy metal content in the products of vermicomposting [38, 61, 63, 69–71]. Deolalikar et al. [135] suggested that increase in heavy metal concentrations of the final feed mixtures of vermicomposting may be due to decline in the volume and weight in the final feed mixtures. Earthworm casts obtained from cultivated lands and sewage soils have higher concentration of heavy metals [126]. Yadav and Garg [38] reported increased content of heavy metals during vermicomposting of industrial solid wastes and weeds by *E. fetida*. The authors revealed that mineralization and reduction of waste biomass during vermicomposting process may increase heavy metal content in the final feed mixtures. Increase in heavy metals (Zn, Fe, Mn, Ni) during vermicomposting of paper mill sludge have also been observed by Elvira et al. [84]. Although there was an increase in the heavy metal concentrations in vermicomposting process but the contents were less than the international standards, which indicated that the vermicompost can be applied for agricultural purposes without any harmful effects.

Conclusion and Future Prospects

From the information provided in this review, it can be concluded that vermicomposting is economically sound, environmentally safe technology for organic waste degradation. The earthworms improved the physico-chemical characteristics of waste materials, indicating that the application of vermicompost can significantly improve the fertility of soil. In most of the studies, organic waste when applied in combination with other bulking material has improved the growth of earthworms as well as quality of the final vermicompost. The earthworm-microbe interaction is interdependent and the relationship between earthworm and microbes can play a major role in producing high quality manure. The final vermicompost was higher in available nutrients than traditional compost and has a huge potential for agricultural purposes. So, farmers must be educated regarding the useful role of earthworms as waste managers and biofertilizer producers. Keeping the above advantages in mind, vermicompost in near future should be applied to agricultural crops to replace chemical fertilizers. The organic farming continues to grow at world level and the crop made by organic fertilizers sustains the yield and fertility of soil. The studies reported by many authors described earthworms as ecological engineers in utilizing the organic wastes and also the final vermicompost as a powerful biofertilizer for sustainable development.

Acknowledgements The authors acknowledge University Grants Commission (UPE and BSR) for financial support and Head, Department of Botanical and Environmental Sciences, Guru Nanak Dev University, Amritsar for necessary laboratory facilities.

Author contributions SAB collected, reviewed the literature and drafted the manuscript. JS improved the quality of the manuscript. APV provided guidance and finalized the manuscript. All authors read and approved final manuscript.

Compliance with Ethical Standards

Conflict of interest The authors declare that they have no competing interests.

References

1. Chalmin, P., Gaillochet, C.: From waste to resource, An abstract of world waste survey. Cyclope, Veolia Environmental Services, Edition Economica, France (2009)
2. Pappu, A., Saxena, M., Asolekar, S.R.: Solid wastes generation in India and their recycling potential in building materials. Building Environ. **42**, 2311–2320 (2007)
3. Sarkhel, P., Banarjee, S.: Municipal solid waste management, source-seperated waste and stakeholder's attitude: a contingent valuation study. Environ. Dev. Sustain. **12**, 611–630 (2009)
4. Ostos, J.C., Lopez-Garrido, R., Murillo, J.M., Lopez, R.: Substitution of peat for municipal solid waste and sewage sludge based composts in nursery growing media: effect on growth and nutrition of the native shrub *Pistacia lentiscus*. Bioresour. Technol. **99**, 1793–1800 (2008)

5. Bhat, S.A., Singh, J., Vig, A.P.: Potential utilization of bagasse as feed material for earthworm *Eisenia fetida* and production of vermicompost. Springerplus **4**, 11 (2015)
6. Atiyeh, R.M., Arancon, N., Edwards, C.A., Metzger, J.D.: The influence of earthworm processed pig manure on the growth and productivity of marigolds. Bioresour. Technol. **81**, 103–108 (2001)
7. Martin, J.P.: Darwin on earthworms: the formation of vegetable moulds. Bookworm Publishing, Ontario (1976)
8. Julka, J.M.: Diversity and distribution of exotic earthworms (*Annelida, Oligochaeta*) in India. A review. In: Chaudhuri, Priyasankar, Singh, S.M. (eds.) Biology and ecology of tropical earthworms, pp. 73–83. Discovery Publishing House New Delhi, India (2014)
9. Munnoli, P.M., Teixeira da Silva, J.A., Bhosle, S.: Dynamics of the soil—earthworm–plant relationship: a review. Dyn. Soil Dyn. Plant **4**, 1–21 (2010)
10. Yasir, M., Aslam, Z., Kim, S.W., Lee, S.W., Jeon, C.O., Chung, Y.R.: Bacterial community composition and chitinase gene diversity of vermicompost with antifungal activity. Bioresour. Technol. **100**, 4396–4403 (2009)
11. Vaz-Moreira, I., Maria, M.E., Silva, C.M., Nunes, O.C.: Diversity of bacterial isolates from commercial and homemade composts. Microbial. Ecol. **55**, 714–722 (2008)
12. Elmer, W.H.: Influence of earthworm activity on soil microbes and soilborne diseases of vegetables. Plant Dis. **93**, 175–179 (2009)
13. Rouelle, J.: Introduction of an amoeba and *Rhizobium Japonicum* into the gut of *Eisenia fetida* (Sav.) and *Lumbricus terrestris* L. In: Satchell, J.E. (ed.) Earthworm ecology: from darwin to vermiculture, pp. 375–381. Chapman and Hall, New York (1983)
14. Madsen, E.L., Alexander, M.: Transport of *Rhizobium* and *Pseudomonas* through soil. Soil Sci. Soc. Am. J. **46**, 557–560 (1982)
15. Singleton, D.R., Hendrix, P.F., Coleman, D.C., Whitman, W.B.: Identification of uncultured bacteria tightly associated with the intestine of the earthworm *Lumbricus rubellus* (Lumbricidae; Oligochaeta). Soil Biol. Biochem. **35**, 1547–1555 (2003)
16. Gopal, M., Gupta, A., Sunil, E., Thomas, V.G.: Amplification of plant beneficial microbial communities during conversion of coconut leaf substrate to vermicompost by *Eudrilus* sp. Curr. Microbiol. **59**, 15–20 (2009)
17. Khambata, S.R., Bhat, J.V.: Studies on a new oxalatedecomposing bacterium, *Pseudomonas oxalaticus*. J. Bacteriol. **66**, 505–507 (1953)
18. Doube, B.M., Stephens, P.M., Davorena, C.W., Ryderb, M.H.: Interactions between earthworms, beneficial soil microorganisms and root pathogens. Appl. Soil Ecol. **1**, 3–10 (1994)
19. Bouche, M.B.: Strategies lombriciennes. In: Lohm, U., Persson, T. (eds.), Soil organisms as components of ecosystems. Biological Bulletin, Stockholm **25**, 122–132 (1977)
20. Edwards, C.A., Lofty, J.R.: Biology of earthworms. Chapman and Hall, London (1972)
21. Chowdappa, P., Biddappa, C.C., Sujatha, S.: Efficient recycling of organic wastes in arecanut (*Areca catechu* L.) and cocoa (*Theobroma cacao* L.) plantation through vermicomposting. Indian. J. Agric. Sci. **69**, 563–566 (1999)
22. Ismail, S.A.: Earthworms in soil fertility management. In: Thampan, P.K. (ed.) Organic Agriculture. pp 77–100 (1995)
23. Edwards, C.A., Fletcher, K.E.: Interaction between earthworms and microorganisms in organic matter breakdown. Agric. Ecosyst. Environ. **20**, 235–249 (1988)
24. Vivas, A., Moreno, B., Garcia-Rodriguez, S., Benitez, E.: Assessing the impact of composting and vermicomposting on bacterial community size and structure, and functional diversity of an olive-mill waste. Bioresour. Technol. **100**, 1319–1326 (2009)
25. Edwards, C.A., Bohlen, P.J.: Biology and ecology of earthworms, 3rd edn. Chapman and Hall, London (1996)
26. Brown, G.G., Barois, I., Lavelle, P.: Regulation of soil organic matter dynamics and microbial activity in the drilosphere and the role of interactions with other edaphic functional domains. Eur. J. Soil Biol. **36**, 177–198 (2000)
27. Zhang, B.G., Li, G.T., Shen, T.S., Wang, J.K., Sun, Z.: Changes in microbial biomass C, N, and P and enzyme activities in soil incubated with the earthworms *Metaphire guillelmi* or *Eisenia foetida*. Soil Biol. Biochem. **32**, 2055–2062 (2000)
28. Aira, M., Monroy, F., Dominguez, J.: Earthworms strongly modify microbial biomass and activity triggering enzymatic activities during vermicomposting independently of the application rates of pig slurry. Sci. Total Environ. **385**, 252–261 (2007)
29. Aira, M., Dominguez, J.: Optimizing vermicomposting of animal wastes: effects of rate of manure application on carbon loss and microbial stabilization. J. Environ. Manage. **88**, 1525–1529 (2008)
30. Monson, C.C., Damodharan, G., Kumar, S., Kanakasbai, V.: Composing of kitchen waste using in vessel and vermibeds. Proceedings of international conference on cleaner tech and environmental management, 4–6th January (pp. 678–682). Pondichery Engineering College, Pondichery (2007)
31. Kale, R.D., Mallesh, B.C., Kubra, B., Bhagyaraj, D.J.: Influence of vermicompost application on available micronutrients and selected microbial populations in paddy field. Soil Biol. Biochem. **24**, 1317–1320 (1992)
32. Chen, Y., Zhang, Y., Zhang, Q., Xu, L., Li, R., Luo, X., Zhang, X., Tong, J.: Earthworms modify microbial community structure and accelerate maize stover decomposition during vermicomposting. Environ. Sci. Pollut. Res. **22**, 17161–17170 (2015)
33. Aira, M., Monroy, F., Dominguez, J.: Detritivorous earthworms directly modify the structure, thus altering the functioning of a microdecomposer food web. Soil Biol. Biochem. **40**, 2511–2516 (2008)
34. Koubova, A., Chronakova, A., Pizl, V., Sanchez-Monedero, M.A., Elhottova, D.: The effects of earthworms *Eisenia* spp. on microbial community are habitat dependent. Eur. J. Soil Biol. **68**, 42–55 (2015)
35. Sampedro, L., Dominguez, J.: Stable isotope natural abundances (δ^{13}C and δ^{15}N) of the earthworm *Eisenia fetida* and other soil fauna living in two different vermicomposting environments. Appl. Soil Ecol. **38**, 91–99 (2008)
36. Munnoli, P.M., Bhosle, S.: Water-holding capacity of earthworms' vermicompost made of sugar industry waste (press mud) in mono and poly culture vermireactors. Environmentalist **31**, 394–400 (2011)
37. Garg, V.K., Gupta, R., Yadav, A.: Potential of vermicomposting technology in solid waste management. In: Pandey, A., et al. (eds.) Current developments in solid state fermentation. Asia-Tech, pp. 468–511. Publishers Inc., New Delhi (2007)
38. Yadav, A., Garg, V.K.: Nutrient recycling from industrial solid wastes and weeds by vermiprocessing using earthworms. Pedosphere **23**, 668–677 (2013)
39. Neuhauser, E.F., Hartenstein, R., Kaplan, D.L.: Growth of the earthworm *Eisenia foetida* in relation to population density and food rationing. OIKOS **35**, 93–98 (1980)
40. Ndegwa, P.M., Thompson, S.A.: Effect of C-to-N ratio on vermicomposting of biosolids. Bioresour. Technol. **75**, 7–12 (2000)
41. Tripathi, G., Bhardwaj, P.: Comparative studies on biomass production, life cycles and composting efficiency of *Eisenia foetida* (Savigny) and *Lampito mauritii* (Kinberg). Bioresour. Technol. **92**, 275–278 (2004)

42. Gajalakshmi, S., Ramasamy, E.V., Abbasi, S.A.: Composting–vermicomposting of leaf litter ensuing from the trees of mango (*Mangifera indica*). Bioresour. Technol. **96**, 1057–1061 (2005)
43. Singh, J., Kaur, A., Vig, A.P.: Bioremediation of distillery sludge into soil-enriching material through vermicomposting with the help of *Eisenia fetida*. Appl. Biochem. Biotechnol. **174**, 1403–1419 (2014)
44. Suthar, S.: Bioconversion of post-harvest residues and cattle shed manure into value added products using earthworm *Eudrilus eugeniae*. Ecol. Eng. **32**, 206–214 (2008)
45. Dominguez, J., Edwards, C. A.: Effects of stocking rate and moisture contents on the growth and maturation of *Eisenia anderi* (*Oligochaeta*) in pig manure. Soil Biol. Biochem. **29**, 143–746 (1997)
46. Edwards, C.A., Dominguez, J., Neuhauser, E.F.: Growth and reproduction of *Perionyx excavatus* (*Perr.*) (*Megascolecidae*) as factors in organic waste management. Biol. Fert. Soils. **27**, 155–161 (1998)
47. Garg, V.K., Kaushik, P., Yadav, Y.K.: Effect of stocking density and food quality on the growth and fecundity of an epigeic earthworm (*Eisenia fetida*) during vermicomposting. Environmentalist **28**, 483–488 (2008)
48. Suthar, S.: Growth and fecundity of earthworm, *Perionyx excavates* and *Perionyx sansibaricus* in cattle waste solids. Environ. Sci. Technol. **29**, 78–84 (2009)
49. Reinecke, A.J., Viljoen, S.A., Saayman, R.J.: The suitability of *Eudrilus eugeniae, Perionyx excavatus* and *Eisenia foetida* (*Oligochaeta*) for vermicomposting in Southern Africa in terms of their temperature requirements. Soil Biol. Biochem. **24**, 1295–1307 (1992)
50. Reinecke, A.J., Venter, J.M.: Moisture preference, growth and reproduction of the compost worm *Eisenia fetida* (*Oligochaeta*). Biol. Fert. Soils. **3**, 135–141 (1987)
51. Xie, D., Wu, W., Hao, X., Jiang, D., Li, X., Bai, L.: Vermicomposting of sludge from animal wastewater treatment plant mixed with cow dung or swine manure using *Eisenia fetida*. Environ. Sci. Pollut. Res. **23**, 7767–7775 (2016)
52. Das, S., Deka, P., Goswami, L., Sahariah, B., Hussain, N., Bhattacharya, S.S.: Vermiremediation of toxic jute mill waste employing *Metaphire posthuma*. Environ. Sci. Pollut. Res. **23**, 15418–15431 (2016)
53. Malinska, K., Zabochnicka-Swiatek, M., Caceres, R., Marfa, O.: The effect of precomposted sewage sludge mixture amended with biochar on the growth and reproduction of *Eisenia fetida* during laboratory vermicomposting. Ecol. Eng. **90**, 35–41 (2016)
54. Yadav, A., Suthar, S., Garg, V.K.: Dynamics of microbiological parameters, enzymatic activities and worm biomass production during vermicomposting of effluent treatment plant sludge of bakery industry. Environ. Sci. Pollut. Res. **22**, 14702–14709 (2015)
55. Hanc, A., Vasak, F.: Processing separated digestate by vermicomposting technology using earthworms of the genus *Eisenia*. Int. J. Environ. Sci. Technol. **12**, 1183–1190 (2015)
56. Suthar, S., Kumar, K., Mutiyar, P.K.: Nutrient recovery from compostable fractions of municipal solid wastes using vermitechnology. J. Mater. Cycles Waste. Manage. **17**, 174–184 (2015)
57. Xing, M., Lv, B., Zhao, C., Yang, J.: Towards understanding the effects of additives on the vermicomposting of sewage sludge. Environ. Sci. Pollut. Res. **22**, 4644–4653 (2015)
58. Fu, X., Huang, K., Chen, X., Li, F., Cui, G.: Feasibility of vermistabilization for fresh pelletized dewatered sludge with earthworms *Bimastus parvus*. Bioresour. Technol. **175**, 646–650 (2015)
59. Fu, X., Cui, G., Huang, K., Chen, X., Li, F., Zhang, X., Li, F.: Earthworms facilitate the stabilization of pelletized dewatered sludge through shaping microbial biomass and activity and community. Environ. Sci. Pollut. Res. **23**, 4522–4530 (2016)
60. Bhat, S.A., Singh, J., Vig, A.P.: Vermistabilization of sugar beet (*Beta vulgaris* L) waste produced from sugar factory using earthworm *Eisenia fetida*: Genotoxic assessment by *Allium cepa* test. Environ. Sci. Pollut. Res. **22**, 11236–11254 (2015)
61. Varma, V.S., Yadav, J., Das, S., Kalamdhad, A.S.: Potential of waste carbide sludge addition on earthworm growth and organic matter degradation during vermicomposting of agricultural wastes. Ecol. Eng. **83**, 90–95 (2015)
62. Rajpal, A., Bhargava, R., Chopra, A.K., Kumar, T.: Vermistabilization and nutrient enhancement of anaerobic digestate through earthworm species *Perionyx excavatus* and *Perionyx sansibaricus*. J. Mater. Cycle. Waste Manage. **16**, 219–226 (2014)
63. Hanc, A., Chadimova, Z.: Nutrient recovery from apple pomace waste by vermicomposting technology. Bioresour. Technol. **168**, 240–244 (2014)
64. Lim, P.N., Wu, T.Y., Clarke, C., Nik Daud, N.N.: A potential bioconversion of empty fruit bunches into organic fertilizer using *Eudrilus eugeniae*. Int. J. Environ. Sci. Technol. **2**, 2533–2544 (2015)
65. Suthar, S., Gairola, S.: Nutrient recovery from urban forest leaf litter waste solids using *Eisenia fetida*. Ecol. Eng. **71**, 660–666 (2014)
66. Bhat, S.A., Singh, J., Vig, A.P.: Genotoxic assessment and optimization of Pressmud with the help of exotic earthworm *Eisenia fetida*. Environ. Sci. Pollut. Res. **21**, 8112–8123 (2014)
67. Goswami, L., Sarkar, S., Mukherjee, S., Das, S., Barman, S., Raul, P., Bhattacharyya, P., Mandal, N.C., Bhattacharya, S., Bhattacharya, S.S.: Vermicomposting of tea factory coal ash: metal accumulation and metallothionein response in *Eisenia fetida* (Savigny) and *Lampito mauritii* (Kinberg). Bioresour. Technol. **166**, 96–102 (2014)
68. Bhat, S.A., Singh, J., Vig, A.P.: Vermiremediation of dyeing sludge from textile mill with the help of exotic earthworm *Eisenia fetida* Savigny. Environ. Sci. Pollut. Res. **20**, 5975–5982 (2013)
69. Najar, I.A., Khan, A.B.: Management of fresh water weeds (macrophytes) by vermicomposting using *Eisenia fetida*. Environ. Sci. Pollut. Res. **20**, 6406–6417 (2013)
70. Azizi, A.B., Lim, M.P.M., Noor, Z.M., Abdullah, N.: Vermiremoval of heavy metal in sewage sludge by utilising *Lumbricus rubellus*. Ecotoxicol. Environ. Saf. **90**, 13–20 (2013)
71. Singh, A., Jain, A., Sarma, B.K., Abhilash, P.C., Singh, H.B.: Solid waste management of temple floral offerings by vermicomposting using *Eisenia fetida*. Waste Manag. **33**, 1113–1118 (2013)
72. Suthar, S., Mutiyar, P.K., Singh, S.: Vermicomposting of milk processing industry sludge spiked with plant wastes. Bioresour. Technol. **116**, 214–219 (2012)
73. Vig, A.P., Singh, J., Wani, S.H., Dhaliwal, S.S.: Vermicomposting of tannery sludge mixed with cattle dung into valuable manure using earthworm *Eisenia fetida* (Savigny). Bioresour. Technol. **102**, 7941–7945 (2011)
74. Singh, J., Kaur, A., Vig, A.P., Rup, P.J.: Role of *Eisenia fetida* in rapid recycling of nutrients from bio sludge of beverage industry. Ecotoxicol. Environ. Saf. **73**, 430–435 (2010)
75. Kaur, A., Singh, J., Vig, A.P., Dhaliwal, S.S., Rup, P.J.: Cocomposting with and without *Eisenia fetida* for conversion of toxic paper mill sludge to a soil conditioner. Bioresour. Technol. **101**, 8192–8198 (2010)

76. Singh, S., Bhat, S.A., Singh, J., Kaur, R., Vig, A.P.: Vermistabilization of thermal power plant fly ash using *Eisenia fetida*. J. Ind. Pollut. Contr. **32**, 554–561 (2016)
77. Suthar, S., Pandey, B., Gusain, R., Gaur, R.Z., Kumar, K.: Nutrient changes and biodynamics of *Eisenia fetida* during vermicomposting of water lettuce (*Pistia* sp.) biomass: a noxious weed of aquatic system. Environ. Sci. Pollut. Res. **24**, 199–207 (2017)
78. Yadav, A., Garg, V.K.: Vermiconversion of biogas plant slurry and parthenium weed mixture to manure. Int. J. Recycl. Org. Waste Agricult. **5**, 301–309 (2016)
79. Sharma, K., Garg, V.K.: Management of food and vegetable processing waste spiked with buffalo waste using earthworms (*Eisenia fetida*). Environ. Sci. Pollut. Res. doi:10.1007/s11356-017-8438-2
80. Parthasarathi, K., Balamurugan, M., Prashija, K.V., Jayanthi, L., Basha, S.A.: Potential of *Perionyx excavatus* (Perrier) in lignocellulosic solid waste management and quality vermifertilizer production for soil health. Int. J. Recycl. Org. Waste Agricult. **5**, 65–86 (2016)
81. Garg, V.K., Gupta, R.: Optimization of cow dung spiked pre-consumer processing vegetable waste for vermicomposting using *Eisenia fetida*. Ecotoxicol. Environ. Saf. **74**, 19–24 (2011)
82. Khwairakpam, M., Bhargava, R.: Bioconversion of filter mud using vermicomposting employing two exotic and one local earthworm species. Bioresour. Technol. **100**, 5846–5852 (2009)
83. Garg, V.K., Yadav, Y.K., Sheoran, A., Chand, S., Kaushik, P.: Livestock excreta management through vermicomposting using an epigeic earthworm *Eisenia foetida*. Environmentalist **26**, 269–276 (2006)
84. Elvira, C., Sampedro, L., Benitez, E., Nogales, R.: Vermicomposting of sludges from paper mill and dairy industries with *Eisenia andrei*: a pilot scale study. Bioresour. Technol. **63**, 205–211 (1998)
85. Hogg, D., Eaviono, E., Caimi, V., Amlinger, F., Devliegher, W., Brinton, W., Antler, S.: Comparison of composts standards within the programme (WARP). Oxon (2002)
86. Jadia, C.D., Fulekar, M.H.: Vermicomposting of vegetable waste: A biophysicochemical process based on hydro-operating bioreactor. Afri. J. Biotechnol. **7**, 3723–3730 (2008)
87. Datar, M.T., Rao, M.N., Reddy, S.: Vermicomposting-a technological option for Solid waste management. J. Solid Waste Technol. Manag. **24**, 89–93 (1997)
88. Rynk, R.M., Kamp, V.D., Willson, G.G., Singley, M.E., Richard, T.L., Kolega, J.J., Gouin, F.R., Laliberty, J.L., Kay, D., Murphy, D.H., Hoitink, A.J., Brinton, W.F.: In: Rynk, R. (ed.) On-farm composting handbook, p. 186. NRAES-54 Natural Resource, Agriculture and Engineering Service (1992)
89. Muthukumaravel, K., Amsath, A., Sukumaran, M.: Vermicomposting of vegetable waste using cow dung. Eur. J. Chem. **5**, 810–813 (2008)
90. Singh, N.B., Khare, A.K., Bhargava, D.S., Bhattacharya, S.: Effect of initial substrate pH on vermicomposting using *Perionyx excavatus*. Appl. Ecol. Environ. Res. **4**, 85–97 (2005)
91. Lazcano, C., Gomez-Brandon, M., Dominguez, J.: Comparison of the effectiveness of composting and vermicomposting for the biological stabilization of cattle manure. Chemosphere. **72**, 1013–1019 (2008)
92. Lasaridi, K., Protopapa, I., Kotsou, M., Pilidis, G., Manios, T., Kyriacou, A.: Quality assessment of composts in the green market: the need for standards and quality assurance. J. Environ. Manag. **80**, 58–65 (2003)
93. Hait, S., Tare, V.: Vermistabilization of primary sewage sludge. Bioresour. Technol. **102**, 2812–2820 (2011)
94. Garg, P., Gupta, A., Satya, S.: Vermicomposting of different types of waste using *Eisenia foetida*: a comparative study. Bioresour. Technol. **97**, 391–395 (2006)
95. Karmegam, N., Daniel, T.: Investigating efficiency of *Lampito mauritii* (Kinberg) and *Perionyx ceylanensis* Michaelsen for vermicomposting of different types of organic substrates. Environmentalist **29**, 287–300 (2009)
96. Kaviraj, Sharma, S.: Municipal solid waste management through vermicomposting employing exotic and local species of earthworms. Bioresour. Technol. **90**, 169–173 (2003)
97. Hayawin, Z.N., Khalil, H.P.S.A., Jawaid, M., Ibrahim, M.H., Astimar, A.A.: Exploring chemical analysis of vermicompost of various oil palm fibre wastes. Environmentalist **30**, 273–278 (2010)
98. Garg, V.K., Kaushik, P.: Vermistabilization of textile mill sludge spiked with poultry droppings by an epigeic earthworm *Eisenia foetida*. Bioresour. Technol. **96**, 1063–1071 (2005)
99. Venkatesh, R.M., Eevera, T.: Mass reduction and recovery of nutrients through vermicomposting of fly ash. Appl. Ecol. Environ. Res. **6**, 77–84 (2008)
100. Ravindran, B., Dinesh, S.L., John Kennedy, L., Sekaran, G.: Vermicomposting of solid waste generated from leather industries using Epigeic Earthworm *Eisenia foetida*. Appl. Biochem. Biotechnol. **151**, 480–488 (2008)
101. Senesi, N.: Composted materials as organic fertilizers. Sci. Total Environ. **81**, 521–524 (1989)
102. Bhat, S.A., Singh, J., Vig, A.P.: Instrumental characterization of organic wastes for evaluation of vermicompost maturity. J. Anal. Sci. Technol. **8**, 2 (2017)
103. Ruz-Jerez, B.E., Ball, P.R., Tillman, R.W.: Laboratory assessment of nutrient release from a pasture soil receiving grass or clover residues, in the presence or absence of *Lumbricus rubellus* or *Eisenia fetida*. Soil Biol. Biochem. **24**, 1529–1534 (1992)
104. Ozawa, T., Risal, C.P., Yanagimoto, R.: Increase in the nitrogen content of soil by the introduction of earthworms into soil. Soil Sci. Plant Nutri. **51**, 917–920 (2005)
105. Cynthia, J.M., Rajeshkumar, K.T.: A study on sustainable utility of sugar mill effulent to vermicompost. Adv. Appl. Sci. Res. **3**, 1092–1097 (2012)
106. Suthar, S.: Vermicomposting potential of *perionyx sansibaricus* (Perrier) in different waste materials. Bioresour. Technol. **98**, 1231–1237 (2007)
107. Viel, M., Sayag, D., Andre, L.: Optimization of agricultural industrial waste management through in-vessel composting. In: de Bertoldi, M.. (ed.), Compost: production, quality and use. Elsevier Applied Science, Essex, pp. 230–237 (1987)
108. Plaza, C., Nogales, R., Senesi, N., Benitez, E., Polo, A.: Organic matter humification by vermicomposting of cattle manure alone and mixed with two phase olive pomace. Bioresour. Technol. **99**, 5085–5089 (2008)
109. Yadav, A., Garg, V.K.: Vermicomposting—an effective tool for the management of invasive weed *Parthenium hysterophorus*. Bioresour. Technol. **102**, 5891–5895 (2011)
110. Benitez, E., Nogales, R., Elvira, C., Masciandaro, G., Ceccanti, B.: Enzyme activities as indicators of the stabilization of sewage sludge composting with *Eisenia fetida*. Bioresour. Technol. **67**, 297–303 (1999)
111. Kumar, R., Verma, D., Singh, B.L., Kumar, U., Shweta: Composting of sugar-cane waste by-products through treatment with microorganisms and subsequent vermicomposting. Bioresour. Technol. **101**, 6707–6711 (2010)
112. Hesse, P.R.: A textbook of soil chemical analysis. Chemical Publishing Co., Inc, New York (1971)
113. Hameeda, B., Rupela, O.P., Reddy, G., Satyavani, K.: Application of plant growth-promoting bacteria associated with composts and macrofauna for growth promotion of Pearl

millet (*Pennisetum glaucum* L.). Biol. Fertil. Soils. **43**, 221–227 (2006)
114. Pramanik, P., Ghosh, G.K., Ghosal, P.K., Banik, P.: Changes in organic—C, N, P and K and enzyme activities in vermicompost of biodegradable organic wastes under limiting and microbial inoculants. Bioresour. Technol. **98**, 2485–2494 (2007)
115. Suthar, S., Singh, S.: Feasibility of vermicomposting in biostabilization of sludge from a distillery industry. Sci. Total Environ. **394**, 237–243 (2008)
116. Yadav, A., Garg, V.K.: Feasibility of Nutrient recovery from industrial sludge by vermicomposting technology. J. Hazard. Mater. **168**, 262–268 (2009)
117. Vinotha, S.P., Parthasarathi, K., Ranganathan, L.S.: Enhanced phosphatases activity in earthworm casts is more of microbial origin. Current Sci. **79**, 1158–1159 (2000)
118. Ravindran, B., Sekaran, G.: Bacterial composting of animal fleshing generated from tannery industries. Waste Manage. **30**, 2622–2630 (2010)
119. Orozco, F.H., Cegarra, J., Trujillo, L.M., Roig, A.: Vermicomposting of coffee pulp using the earthworm *Eisenia foetida*: effects on C and N contents and the availability of nutrients. Biol. Fert. Soils. **22**, 162–166 (1996)
120. Brady, N.C., Weil, R.R.: In: The nature and properties of soils 13th edn. Pearson Education, Singapore. p. 960 (2002)
121. Kızılkaya, R.: The role of different organic wastes on zinc bioaccumulation by earthworm *Lumbricus terrestris* L. (*Oligochaeta*) in successive Zn added soil. Ecol. Eng. **25**, 322–331 (2005)
122. Alloway, B.J., Ayers, D.C.: Chemical principles of environmental pollution. Chapman & Hall, Alden Press, Oxford (1994)
123. Saxena, M., Chauhan, A., Ashokan, P.: Fly ash vermicomposting from non-ecofriendly organic wastes. Pollut. Res. **17**, 5–11 (1998)
124. Jain, K., Singh, J., Chauhan, L.K., Murthy, R.C., Gupta, S.K.: Modulation of flyash-induced genotoxicity in *Vicia faba* by vermicomposting. Ecotoxicol. Environ. Safe. **59**, 89–94 (2004)
125. Gupta, S.K., Tewari, A., Srivastava, R., Murthy, R.C., Chandra, S.: Potential of *Eisenia fetida* for sustainable and effective vermicomposting of fly ash. Water Air Soil Pollut. **163**, 293–302 (2005)
126. Shasmansouri, M.R., Pourmoghadas, H., Parvaresh, A.R., Alidadi, H.: Heavy metals bioaccumulation by Iranian and Australian Earthworms (*Eisenia fetida*) in the sewage sludge vermicomposting. Iranian J. Environ. Health Sci. Eng. **2**, 28–32 (2005)
127. Vermeulen, F., Van den Brink, N.W., DHave, H., Mubiana, V.K., Blust, R., Bervoets, L., De Coen, W: Habitat type-based bioaccumulation and risk assessment of metal and As contamination in earthworms, beetles and woodlice. Environ. Pollut. **157**, 3098–3105 (2009)
128. Li, L., Xu, Z., Wu, J., Tian, G.: Bioaccumulation of heavy metals in the earthworm *Eisenia fetida* in relation to bioavailable metal concentrations in pig manure. Bioresour. Technol. **101**, 3430–3436 (2010)
129. Soobhany, N., Mohee, R., Garg, V.K.: Comparative assessment of heavy metals content during the composting and vermicomposting of municipal solid waste employing *Eudrilus eugeniae*. Waste Manage. **39**, 130–145 (2015)
130. Soobhany, N., Mohee, R., Garg, V.K.: Experimental process monitoring and potential of *Eudrilus eugeniae* in the vermicomposting of organic solid waste in Mauritius. Ecol. Eng. **84**, 149–158 (2015)
131. Singh, J., Kaur, A.: Vermidegradation for faster remediation of chemical sludge and spent carbon generated by soft drink industries. J. Environ. Sci. Sustain. **1**, 13–20 (2013)
132. Fischer, E., Molnar, L.: Environmental aspects of the chloragogenous tissue of earthworm. Soil Biol. Biochem. **24**, 1723–1727 (1992)
133. Gupta, R., Mutiyar, P.K., Rawat, N.K., Saini, M.S., Garg, V.K.: Development of a water hyacinth based vermireactor using an epigeic earthworm *Eisenia foetida*. Bioresour. Technol. **98**, 2605–2610 (2007)
134. Ravindran, B., Contreras-Ramos, S.M., Wong, J.W.C., Selvam, A., Sekaran, G.: Nutrient and enzymatic changes of hydrolysed tannery solid waste treated with epigeic earthworm *Eudrilus eugeniae* and phytotoxicity assessment on selected commercial crops. Environ. Sci. Pollut. Res. **21**, 641–651 (2014)
135. Deolalikar, A.V., Mitra, A., Bhattacharyee, S., Chakraborty, S.: Effect of vermicomposting process on metal content of paper mill solid waste. J. Environ. Sci. Eng. **47**, 81–84 (2005)