Current understanding on industrial organic waste management by employing *Eisenia fetida*

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Abstract: Earthworms have the inherent capability of stabilising different organic waste materials of industrial as well as domestic origin. This review paper depicts the potential of epigeic earthworm species *Eisenia fetida* in the vermistabilisation of various industrial organic wastes such as silk industry waste, herbal pharmaceutical industry sludge, food industry sludge, milk processing industry sludge, tea factory coal ash, sugar mill sludge, cotton industrial waste, paper mill waste, and bio sludge of beverage industry. The analysis of results obtained clearly indicates the suitability of vermicomposting over conventional composting as an alternative technology for management, stabilisation and nutrient recovery from industrial organic waste.

Keywords: *Eisenia fetida*; industrial organic waste; vermicomposting.

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1 Introduction

Industrial waste management is one of the complex problems faced by the developing as well as developed countries. The hale and hearty relationships between man and nature have been largely affected by rapid industrialisation. Both small scale and bigger industrial units dump their waste unscientifically, more often hazardous and toxic that causes pollution to air, water and land. The technical and ecological challenge due to unscientific dumping of industrial organic waste is a matter of concern among scientists around the world. India accounts for 17.99% of the total population of the world that represents at least one in every six people on this planet (Chiranjeevi et al., 2018). The United Nations Development Programme (UNDP) report 2017 revealed that the average national human development index (HDI) for India was 0.640, which directly put India in the medium human development category. A significant increase of nearly 50% was recorded between 1990 and 2017. The quantity of waste generated is directly related to rapid urbanisation and the rise in population also influences quantity and types of waste. With an annual increment of 5%, about 69 million tonnes of solid waste was generated in India per year (Gupta et al., 2015). Only 43 million tonnes is being collected and 12 million tonnes is being subjected to further treatment (Chiranjeevi et al., 2018). Many industries generate both inorganic as well as organic waste.

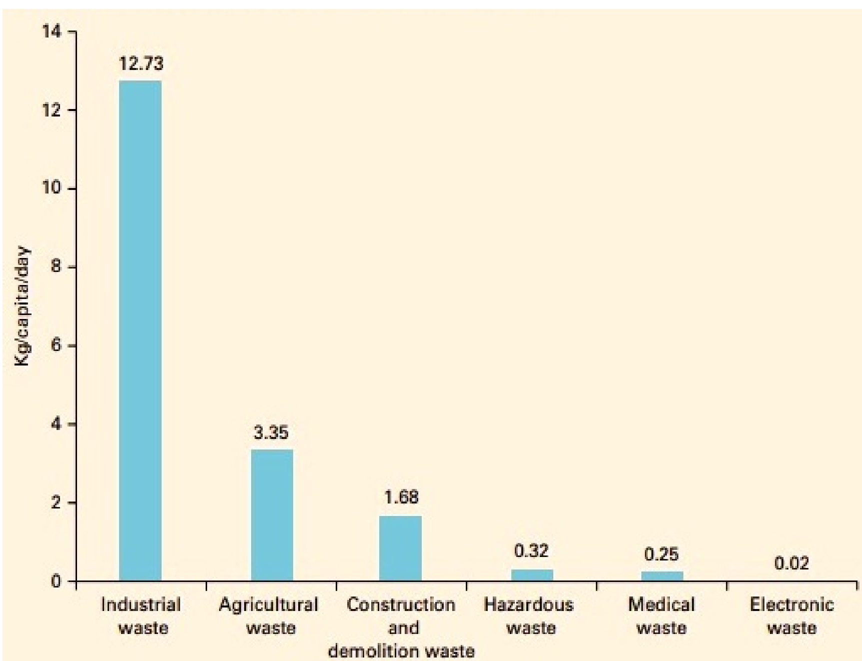
The non-recyclable organic waste can be used as a reasonably good feed for the earthworms in the vermicomposting process. During the vermiconversion of organic waste products earthworms consume, crush and digest the products with the help of both aerobic and anaerobic microflora, stabilising it into a much homogenised, humified and microbially active product. The generated vermicast has desirable aesthetics and it may contain reduced levels of environmental contaminants (Ndegwa and Thompson, 2001), besides being a superior plant growth medium (Aranda et al., 1999). More than 3,920 earthworm species have been reported worldwide so far. In India, 509 species belonging to 67 genera and ten families were reported (Kale and Krishnamoorthy, 1981). Certain species of earthworms viz. *Allolobophora chlorotica*, *Lumbricus terrestris*, *Dendrobaena rubida*, *Eisenia fetida*, *Aporrectodea tuberculata*, and *Eiseniella tetraedra* have been found most efficient in removing a wide range of pollutants from soil.

The objective of the present study is to mainly focus on the vermicomposting potential of the earthworm species *Eisenia fetida* on industrial organic waste generated from different agro-based industries.

2 Generation of industrial organic waste

Industrialisation coupled with population growth and rapid urbanisation has led to a drastic rise in the quantity of industrial organic waste. Generation of waste is a direct consequence of developmental policies adopted by the government. The complexity and quantity of industrial organic waste generation are influenced by economic development and improvement of living standards in the cities (Gidde et al., 2008). As the nations are committed to provide more services and advanced products to its citizens and take part in global trade and exchange, they generate huge amounts of waste to manage by means of treatment and disposal (Figure 1). According to a report prepared by the World Bank (Solid Waste Management, September 20, 2018), the cities around the world generated 2.01 billion tonnes of solid waste, which is close to 0.74 kilograms per person per day. With the rapid growth of these cities and countries, the world is in desperate need of systems to overcome the challenge of growing industrial waste. To keep the citizens healthy and maintain a clean environment, an efficient mechanism for industrial waste management is an essential need of every country. It is important to find a way to address the remediation issues of these organic industrial waste utilising sustainable and more efficient waste management practices (Rong et al., 2017).

Figure 1 Global average waste generation (see online version for colours)



Note: kg = kilogram.

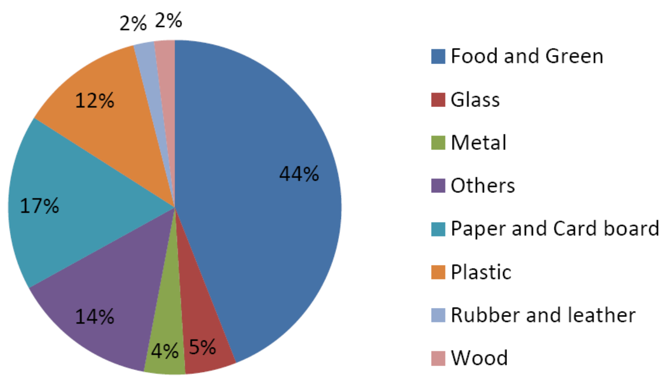
Source: Kaza et al. (2018)

3 Worldwide generation of industrial waste:

The waste management situation of a country evolves when it moves from low-income level to middle-income level. As compared to the residents of developed countries, people residing in developing nations, more specifically the urban poor, are more harshly impacted by unscientifically and unsustainably managed industrial organic waste. In developing countries, over 90% of the waste is either burned openly or disposed of in unregulated dumps. Countries belonging to Central Asia, East Asia and Pacific and the Europe regions contribute 43% of the world's waste by magnitude. Least amount of waste (15%) has been recorded from the Middle East, North Africa and Sub-Saharan Africa regions (Figure 3). In absolute terms, Pacific and East Asia together generated an estimated 468 million tonnes in 2016 whereas 129 million tonnes of waste were recorded from North America and Middle East regions.

If we consider in an international scale, the largest category of waste generation comes under food and green waste, which makes up about 44% of the total waste (Kaza et al., 2018). Different proportions of waste generated through industries are presented in Figure 2.

Figure 2 Composition of industrial waste dominated by agro-industrial waste (see online version for colours)



Source: Kaza et al. (2018)

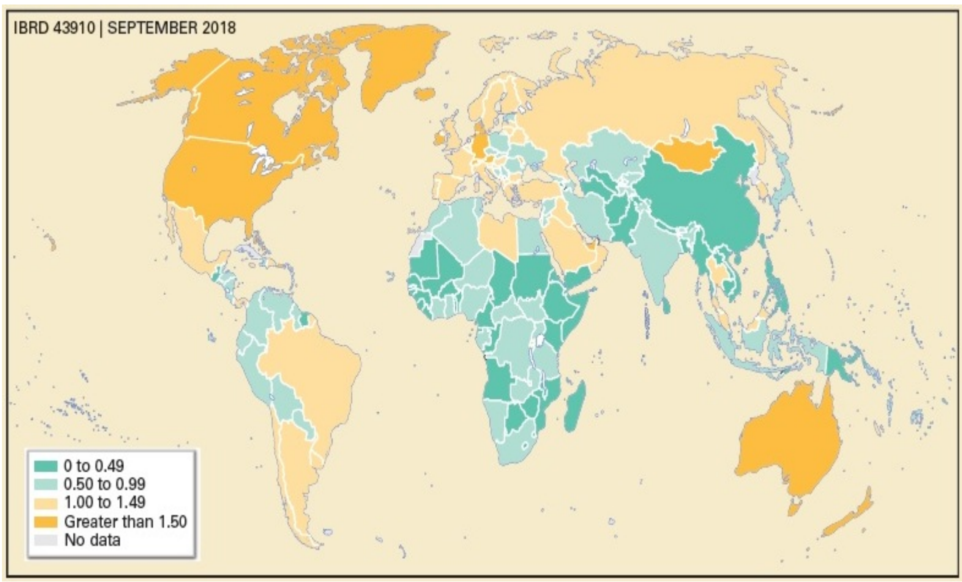
3.1 Generation of industrial waste in developed countries

More urban population indicates more waste generation. Developed countries have the largest urbanised populations and generate more waste per capita and as a whole. Although only 16% of the world's population resides in developed countries they generate 34% or 683 million tonnes of the world (Kaza et al., 2018). The three North American countries – Canada, Bermuda and the USA produce the highest amount of per capita 2.21 kilogram waste per day. However, the trend of waste generation rate is changing and it is expected to be overtaken by developing countries by 2020.

3.2 Generation of industrial waste in developing countries

The developing countries, especially the 'low income' countries, account for 9% of the total population of the world but they contribute only 93 million tonnes which is a mere 5% of the total waste of the world (Kaza et al., 2018). The rapid urbanisation is one of the major causes of the increasing rate of waste generation. The level of waste generation is expected to be triple by 2050 in the developing countries. Since the quantity of waste generation increases with economic development, the developing countries are expected to be producing more industrial waste in the near future.

Figure 3 Per capita waste generation (see online version for colours)



Note: values in kilograms.
Source: Kaza et al. (2018)

4 Physico-chemical characteristics of industrial organic waste

The types of industrial organic waste and their quantities vary from plant to plant depending on the raw material consumed, in-plant control measures, external control measures, house-keeping, waste utilisation, collection and recycling practices. Cultural traditions, economic status, climatic and geographic conditions along with dietary habits of a region determine what type of industry will be required, which ultimately determines the type and nature of waste material produced (Jin et al., 2006). The composition and amounts of solid waste are also greatly affected by multiple factors including socio-economic development of the region. The differences in the composition of waste in low, middle and high-income countries are presented in Table 1.

Table 1 The relative composition of municipal solid waste from low, medium and high-income countries

Parameters (%)	*Low-income country*	*Medium*	*High-income*
Organic (putrescible)	40–85	20–65	20–30
Paper	1–10	15–30	15–40
Plastics	1–5	2–6	2–10
Metal	1–5	1–5	3–13
Glass	1–10	1–10	4–10
Rubber, leather, etc.	1–5	1–5	2–10
Other	15–60	15–50	2–10
Moisture content (%)	40–80	0–60	5–20
Density (kg m^{-3})	250–500	170–330	100–170
Calorific value (kcal kg^{-1})	800–1,100	1,000–1,300	1,500–2,700

Source: Cointreau (2006)

5 Industrial organic waste management through vermicomposting

Vermicomposting is a comparatively new process in the management of industrial organic waste and involves stabilisation of organic waste through consumption by earthworms that converts the organic waste into earthworm castings. The joint action of earthworms and microorganisms is important for a successful vermicomposting experiment. Different studies have mainly focused on the utilisation of earthworms in the stabilisation of organic residues such as sewage sludge, animal manure, crop residues, and industrial waste. However, microbes are responsible for the degradation of organic matter biochemically. One of the prime steps in a vermicomposting experiment is the selection of the right earthworm species since it is directly related to the rate of stabilisation of waste material. Lots of earthworm species have been reported for their potential to be used in industrial organic waste management practices. The earthworm species with high capability to degrade, digest and assimilate organic matter, which are able to withstand a wide range of environmental stress, rapid growth rate and capable of producing large number of cocoons in a short hatching time are the most eligible to be used in vermicomposting experiment (Domínguez and Edwards, 2004).

6 Industrial organic waste management using *Eisenia fetida*

Eisenia fetida, more commonly known as tiger worm or dung worm, is an epigean species of earthworm. It is found extensively in various habitats around the world. Initially, they were found only in Europe, but both intentionally and unintentionally they have been introduced to every other part of the world except Antarctica. *Eisenia fetida* prefers to live among decaying organic matter, such as in the leaf litter, rather than live underground. Because of its well-known adaptability to degrade decaying organic material at a relatively fast rate, it is widely used for the vermicomposting experiment. The potential of *Eisenia fetida* in the vermicomposting of organic waste has been already established by various researchers. Some of the applications of *Eisenia fetida* in industrial organic waste management are discussed below.

6.1 Cotton industrial waste management

Albanell et al. (1988) conducted an experiment in which they mixed sheep manure and cotton industrial waste in 3:1 ratio and subjected to a vermicomposting experiment by employing the earthworm species *Eisenia fetida*. The duration of the experiment was three months. Physico-chemical analysis of the vermicasts was carried out in every two weeks for three months and the results were compared with the same manures in the absence of earthworm (i.e., control treatment). The results revealed that *Eisenia fetida* accelerated the rate of mineralisation of the waste materials. The earthworms converted the waste materials into vermicasts with a higher nutritional value. The castings resulting from the mixture of manure and cotton wastes exhibit a higher degree of humification and good agronomic quality, which is a clear indication that industrial waste generated from cotton industry can be stabilised in the vermicomposting experiment by using the earthworm species *Eisenia fetida*.

6.2 Stabilisation of paper mill waste water sludge

The paper industry is considered as one of the most polluting industries of the world. A huge amount of solid wastes are generated due to pulping and bleaching, the two main steps involved with the manufacturing of paper. The principal solid wastes generated from pulp and paper industries are lime mud, treatment sludges, lime slaker grits, scrubber sludges, boiler and furnace ash and residuals generated from wood processing. Negi and Suthar (2013) studied the vermicomposting potential of *Eisenia fetida* in paper mill wastewater sludge spiked with cow dung at ratios of 0%, 25%, 50%, 75%, and 100%. Five treatments were established to study the changes in microbial and physico-chemical changes. Samples were collected at seven days interval up to day 56, dried for 48 hours in an oven at 60°C and kept in airtight plastic containers at ambient temperature. The results revealed that total organic carbon (TOC), C:N ratio and cellulose content was decreased in the end product due to vermistabilisation of the waste materials. However, the resulting vermicast showed an increase in the values of pH, electrical conductivity (EC) and ash content. Both the micronutrient and macronutrient status of the vermicast were found to be significantly higher than the initial raw materials. Paper mill sludge with 25%–50% of cow dung exhibited a maximum rate of mineralisation. Microbial studies confirmed the increase of fungal, bacterial and actinomycetes population. The high nutritional status of the vermicast indicates the appropriateness of vermistabilised paper mill waste water sludge for the agronomic application.

6.3 Recycling of bio sludge of beverage industry

The approximate net worth of beverage industry is 22.2 billion dollars, which is continuously growing and expected to be doubled in the next 20 years time. This is accompanied by an increase in the generation of organic waste from beverage industries. Most of these industries still dispose of their unstabilised bio sludge in landfills or open dumps that cause severe pollution to land, water and air near the dumping site. Singh et al. (2010) developed a method for rapid recycling of nutrient content from bio sludge generated from the beverage industry. Even after stabilisation for a period of 15 days, the beverage industry bio sludge proved to be carcinogenic when given without mixing anything to *Eisenia fetida*. It was important to find a suitable mixture for the survival of the earthworms. The superiority of the mixture was determined by recording mortality, population build up, growth rate, rate of decomposition and production of cocoon of *Eisenia fetida*. The beverage bio sludge and cattle dung mixture of 50:50 was proved to be suitable for maximum population build up and minimum mortality of the earthworms. Rectangular trays made of plastics (28 × 23 × 6 cm) were used for the experimental setup. To check evaporation and maintain moisture hessian cloths were used. The duration of the experiment was 120 days and samples were collected at 15 days interval for analysis. The vermicast showed an increase in pH, nitrogen, phosphorus and sodium, while potassium, organic carbon and EC declined significantly compared to the control treatment (without earthworm). When earthworms were introduced at 25 g worms/kg feed mixture, 75 days were required for the degradation of 50:50 mixtures. However, the quality of the product was considered to be better when it was obtained after 105–110 days with a feed mixture of 7.5 g worms/kg.

6.4 Nutrient recovery from food industry sludge

A huge amount of liquid and solid wastes are generated from food processing industries around the world. Ecological, as well as economical disposal of these industrial sludges is becoming a major challenge for industries as well as scientists because of the high market price of stabilisation reactors, systems of dehydration and shipping of sludge to dumping sites. The improper and unscientific dumping methods of these sludges result in both economic loss as well as nutrient loss. Yadav and Garg (2009) reported the possibility of exploitation of vermicomposting technology by utilising earthworm species *Eisenia fetida* for nutrient recovery from food industry sludge. Nine vermireactors with a dissimilar percentage of food industry sludge mixed with cow dung were setup for the experiment. The duration of the experiment was three months. Expectedly the earthworms were unable to survive in 100% food industry sludge. The results revealed that pH, organic matter, organic carbon content, C:N ratio were decreased in the vermireactors. However, EC, ash content, nitrogen, potassium and phosphorus contents in all the vermireactors were increased. The content of heavy metal was found to be higher in final vermicompost as compared to the initial raw material. The earthworm biomass was found to be maximum in the control (100% cow dung) and minimum in 30% cow dung + food industry sludge mixture. Production of the cocoon was started from
6th–7th week and the maximum number of the cocoon (57) was recorded in the control. These results are indicative of the production of good quality vermicast from the food industry sludge.

6.5 Stabilisation of milk processing industry sludge

In developing countries like India, the milk processing industry is one of the principal food processing industries. As a result of which it is associated with the generation of a large amount of food processing wastewater. The dairy industry is not severely associated with an environmental problem, but its organic pollutants with a high concentration of suspended solid particles create a disturbance to both terrestrial and aquatic ecosystem (Britz et al., 2006). Vermicomposting of waste water sludge generated from a milk processing industry was carried out by Suthar et al. (2012). To prepare different substrate mixtures for the earthworm *Eisenia fetida* wheat straw, cow dung and sugarcane trash were used. Nine vermibeds were established for the experiment and physico-chemical parameters of the milk processing sludge were observed for 90 days. A homogenised sample of 10 g each was drawn from the vermibins at 15 days interval for the analysis of different parameters. Significant reduction in pH, organic carbon and C:N ratio were recorded in vermicompost whereas, total nitrogen, exchangeable potassium and available phosphorus were increased in the final product. Earthworm biomass and cocoon production were increased in all the vermibeds during the experimental period. Thus, the results confirmed the suitability of *Eisenia fetida* for conversion of milk processing sludge into value-added products.

6.6 Stabilisation of tea factory coal ash

The coal ash generated from the tea factory contains heavy metals, unburnt carbon particles and complex organic compounds (Goswami et al., 2014a). They are also rich in essential elements for plants such as N, P, K and S. The soluble or insoluble forms of heavy metals (Fe, Zn, Pb, Cu, Mn, Cr) found in factory coal ash can act as major sources of pollution near the dumping sites (Goswami et al., 2014a). Looking at the ability of earthworms to accumulate heavy metals in their intestine, Goswami et al. (2014b) exposed the earthworm species *Eisenia fetida* to a few mixtures of tea factory coal ash and cow dung. The efficiency of vermicomposting was compared with aerobic composting. Reproduction pattern of earthworm, the extent of metal accumulation and metallothionein (MT) response of the earthworm were observed. The duration of the experiment was fixed for 60 days. The earthworm number and biomass along with the number of cocoons significantly increased during vermicomposting. The pH of the vermicast decreased and shifted towards neutrality. Total nitrogen content was found to be increased while TOC was decreased in the end product as compared to the compost mixture. Accumulation of heavy metals was observed in the gut of earthworm species. The causal mechanism of heavy metal accumulation in *Eisenia fetida* intestine was confirmed by the increasing concentration of metal inducible metallothionein. The 1:1 mixture of tea factory coal ash and cow dung was found to be most suitable for the proper functioning of *Eisenia fetida*.

6.7 Vermicomposting of silk industry waste

The silk industry is one of the largest groundwater consumers and as a result, it discharges a huge amount of pollutant as waste products (Nguyen et al., 2016). Along with complex and carcinogenic organic chemicals, the silk industry waste contains toxic metals such as Cd, Pb and Cr. Paul et al. (2018) developed an idea for vermistabilisation of silk industry waste by employing *Eisenia fetida*. The researchers studied the biodegradation potential of the earthworm in a few silk industry sludge and cow dung mixtures and the results were compared with normal composting (i.e., without earthworm). The results showed that upon vermicomposting the initial alkaline pH of the industrial waste satisfactorily came near neutralisation point. Compared to aerobic composting the nutrient contents such as N, S, P, Mn and Fe were significantly increased in the vermicast. Reduction up to 60-70% was recorded in heavy metal content (Cr, Cd, Pb, Zn) in the final product of vermicomposting. Cation exchange dynamics and availability of Ca and K were found to be satisfactory in vermicast as compared to aerobic compost. Microbial studies revealed the presence of beneficial microorganisms such as phosphate solubilising and nitrogen-fixing bacteria in the feedstocks. The 1:1 combination of silk industry waste and cow dung was found to be most suitable for the proper functioning of the earthworm species *Eisenia fetida*.

6.8 Vermicomposting of herbal pharmaceutical industry sludge

The side effects of the synthetic pharmaceutical products are well known to all. Due to an increase in health consciousness, people nowadays prefer herbal pharmaceutical products over synthetic products. The industrial unit which uses organic materials as raw materials for the production of herbal pharmaceutical products generates an enormous quantity of spent waste materials during the extraction processes. The unhealthy and unscientific open dumping of these wastes leads to several environmental problems such as green house gas emission, leaching of nutrients to surrounding ecosystems and contamination of native bioresources. Singh and Suthar (2012b) reported the potential of *Eisenia fetida* in the recycling of plant available nutrients from the herbal pharmaceutical industry sludge. By mixing cow dung and herbal pharmaceutical industry waste at a different proportion of five waste mixtures were setup for the experiment including one treatment devoid of the waste material (control). The experiment was carried out for 60 days and samples were drawn at ten days interval for analysis. The high rate of production of cocoons was observed in all the vermibeds. The end product, i.e., vermicast showed a significant increase in-plant available form of nutrients such as nitrate, phosphate, sulphate and available potassium. The microbial studies confirmed the presence of symbiotic fungi, bacteria and actinomycetes in great number. The experiment provided the idea for vermistabilisation of herbal pharmaceutical industry waste and its use in the sustainable soil fertility program.

6.9 Vermiconversion of sugar mill sludge

Sugar industry plays a vital role in the export earnings of India. India holds the second rank among the 83 sugarcane and sugar producing countries (Rao, 2005). The enormous amount of sludge known as press mud is generated mainly from the processing of waste water through the activated sludge process. In developing countries like India because of the prohibitive cost of disposal of sludge, the press mud is either dumped in open field or alongside railway tracks that causes adverse pollution of air, water and land. Since press mud is organic in nature, it contains important nutrients required for the growth and development of plants. The foul odour of the press mud cannot be removed by conventional composting (Sen and Chandra, 2007). The compost so obtained is of lesser nutritive value and the whole process takes 6 months. So along with effective press mud management techniques, it is also important to find out a technology to recover the nutrients present in the press mud. Sangwan et al. (2008b) investigate the vermicomposting potential of *Eisenia fetida* on sugar mill sludge mixed with biogas plant slurry. Different ratios of press mud and biogas plant slurry were prepared for the setup of the experiment and one treatment was kept with cow dung and biogas plant slurry (control) for comparison of the results. The duration of the experiment was fixed for 13 weeks under controlled laboratory conditions. The results revealed a decrease in pH, TOC, total potassium and C:N ratio. However, nitrogen content and total phosphorus were found to be increased in the final product. Earthworm biomass and growth rate was highest in 20% press mud and biogas plant slurry mixture but the addition of 30%–50% of press mud with biogas plant slurry has no negative effect on the quality of vermicast and growth of *Eisenia fetida*. The results clearly indicate the suitability of vermicomposting as an alternate technology for both management and nutrient recovery from sugar mill sludge.

7 Management of industrial organic waste employing *Eisenia fetida* in last decade (2008–2018)

The researchers across the globe are trying to stabilise the industrial organic waste by means of vermicomposting employing *Eisenia fetida* and a lot of works have been done in the previous ten years in this field. Some of the major works regarding vermistabilisation of industrial organic waste in the last ten years are listed in Table 2.

Table 2 Recent works regarding industrial organic waste management employing *Eisenia fetida*

Industrial organic waste type	*Vermicomposting duration*	*References*
Pharmaceutical industry solid waste	60 days	Singh and Suthar (2012a)
Bio sludge of beverage industry	120 days	Singh et al. (2010)
Sugar industry waste	45 days	Khwairakpam and Bhargava (2009)
Food processing industry sludge	90 days	Yadav and Garg (2009)
Textile mill wastewater sludge	84 days	Garg et al. (2008)
Dewatered food industry sludge	91 days	Yadav and Garg (2011)
Sugarcane processing industry	84 days	Sangwan et al. (2008a, 2008b)
Paper mill industry sludge	150 days	Kaur et al. (2010)
Milk processing industry sludge	90 days	Suthar et al. (2012)
Paper mill wastewater sludge	56 days	Negi and Suthar (2013)
Paper-mill sludge	168 days	Fernández-Gómez et al. (2013)
Sugar mill filter cake	45 days	Chen et al. (2010)
Food industry sludge	91 days	Yadav and Garg (2010)
Food processing industry sludge	105 days	Garg and Gupta (2011)
Biogas plant slurry	150 days	Hanc and Vasak (2015)
Sugar industry waste	91 days	Sangwan et al. (2010)
Fruit and vegetable processing industry waste	90 days	Sharma and Garg (2017)
Sago industry solid waste	45 days	Subramanian et al. (2010)
Paper and pulp industry	60 days	Suthar et al. (2014)
Food industry sludge	91 days	Yadav and Garg (2013)
Biogas plant slurry	90 days	Yadav et al. (2013)
Bakery industry sludge	105 days	Yadav et al. (2015)

8 Conclusions

Management of industrial organic waste is a severe problem worldwide. Conventional composting is a possible option but it is time consuming and the final products have lower nutritive values as compared to a value-added product such as vermicompost. Therefore, vermicomposting of industrial organic waste employing suitable earthworm species can be an alternative method for the biomanagement of these wastes. The data obtained from various experimental results present a sound basis for the vermicomposting potential of the epigeic earthworm species *Eisenia fetida* on industrial organic waste. Since the species is cosmopolitan in distribution, researchers can explore its potential on various unexplored industrial wastes in the near future. Besides, the role of microbes during vermicomposting can be explored in order to deliver better value-added products.

References

Albanell, E., Plaixats, J. and Cabrero, T. (1988) 'Chemical changes during vermicomposting (*Eisenia fetida*) of sheep manure mixed with cotton industrial wastes', *Biology and Fertility of Soils*, Vol. 6, No. 3, pp.266–269.

Aranda, E., Barois, I., Arellano, P., Irisson, S., Salazar, T., Rodriguez, K. and Patron, J.C. (1999) 'Vermicomposting in the tropics', in Lavelle, P., Brussard, L. and Hendrix, P. (Eds.): *Earthworm Management in Tropical Agroecosystems*, pp.253–287, CABI Publishing, UK.

Britz, T.J., van Schalkwyk, C. and Hung, Y.T. (2006) 'Treatment of dairy processing wastewaters', in Yapijakis, C., Hung, Y.T., Lo, H.H. and Wang, L.K. (Eds.): *Waste Treatment in the Food Processing Industry*, pp.1–28, CRC Press, Boca Raton, FL.

Chen, G., Zheng, Z., Yang, S., Fang, C., Zou, X. and Luo, Y. (2010) 'Experimental co-digestion of corn stalk and vermicompost to improve biogas production', *Waste Management*, Vol. 30, No. 10, pp.1834–1840.

Chiranjeevi, P., Dahiya, S. and Kumar, N. (2018) 'Waste derived bioeconomy in India: a perspective', *New Biotechnology*, Vol. 40, No. 1, pp.60–69.

Cointreau, S. (2006) 'Occupational and environmental health issues of solid waste management: special emphasis on middle-and lower-income countries', *Urban Papers*, Vol. 1, No. 2, pp.1–48.

Domínguez, J. and Edwards, C.A. (2004) 'Vermicomposting organic wastes: a review', in Hanna, S.H.S. and Mikhail, W.Z.A. (Eds.): *Soil Zoology for Sustainable Development in the 21st Century*, pp.369–395, Linnean Society of London and the Estuarine and Brackish-water Sciences Association, Cairo.

Fernández-Gómez, M.J., Díaz-Raviña, M., Romero, E. and Nogales, R. (2013) 'Recycling of environmentally problematic plant wastes generated from greenhouse tomato crops through vermicomposting', *International Journal of Environmental Science and Technology*, Vol. 10, No. 4, pp.697–708.

Garg, V.K. and Gupta, R. (2011) 'Optimization of cow dung spiked pre-consumer processing vegetable waste for vermicomposting using *Eisenia fetida*', *Ecotoxicology and Environmental Safety*, Vol. 74, No. 1, pp.19–24.

Garg, V.K., Kaushik, P. and Yadav, Y.K. (2008) 'Effect of stocking density and food quality on the growth and fecundity of an epigeic earthworm (*Eisenia fetida*) during vermicomposting', *The Environmentalist*, Vol. 28, No. 4, pp.483–488.

Gidde, M.R., Todkar, V.V. and Kokate, K.K. (2008) 'Municipal solid waste management in emerging mega cities: a case study of Pune city', in *Proceedings of Indo Italian Conference on Green and Clean Environment*, Pune, India, 20–21 March.

Goswami, L., Raul, P., Sahariah, B., Bhattacharyya, P. and Bhattacharya, S.S. (2014a) 'Characterization and risk evaluation of tea industry coal ash for environmental suitability', *CLEAN–Soil, Air, Water*, Vol. 42, No. 10, pp.1470–1476.

Goswami, L., Sarkar, S., Mukherjee, S., Das, S., Barman, S., Raul, P., Bhattacharyya, P., Mandal, N.C., Bhattacharya, S. and Bhattacharya, S.S. (2014b) 'Vermicomposting of tea factory coal ash: metal accumulation and metallothionein response in *Eisenia fetida* (Savigny) and *Lampito mauritii* (Kinberg)', *Bioresource Technology*, Vol. 166, No. 16, pp.96–102.

Gupta, N., Yadav, K.K. and Kumar, V. (2015) 'A review on current status of municipal solid waste management in India', *Journal of Environmental Sciences*, Vol. 37, No. 11, pp.206–217.

Hanc, A. and Vasak, F. (2015) 'Processing separated digestate by vermicomposting technology using earthworms of the genus Eisenia', *International Journal of Environmental Science and Technology*, Vol. 12, No. 4, pp.1183–1190.

Jin, J., Wang, Z. and Ran, S. (2006) 'Solid waste management in Macao: practices and challenges', *Waste Management*, Vol. 26, No. 9, pp.1045–1051.

Kale, R.D. and Krishnamoorthy, R.V. (1981) 'What affects the abundance and diversity of earthworms in soils', *Proc. Indian Acad. Sci.(Anim. Sci.)*, Vol. 90, No. 1, pp.117–121.

Kaur, A., Singh, J., Vig, A.P., Dhaliwal, S.S. and Rup, P.J. (2010) 'Cocomposting with and without *Eisenia fetida* for conversion of toxic paper mill sludge to a soil conditioner', *Bioresource Technology*, Vol. 101, No. 21, pp.8192–8198.

Kaza, S., Yao, L., Bhada-Tata, P. and Van Woerden, F. (2018) *What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050*, World Bank Publications.

Khwairakpam, M. and Bhargava, R. (2009) 'Bioconversion of filter mud using vermicomposting employing two exotic and one local earthworm species', *Bioresource Technology*, Vol. 100, No. 23, pp.5846–5852.

Ndegwa, P.M. and Thompson, S.A. (2001) 'Integrating composting and vermicomposting in the treatment and bioconversion of biosolids', *Bioresource Technology*, Vol. 76, No. 2, pp.107–112.

Negi, R. and Suthar, S. (2013) 'Vermistabilization of paper mill wastewater sludge using *Eisenia fetida*', *Bioresource Technology*, Vol. 128, No. 1, pp.193–198.

Nguyen, N.H., Beeton, R.J. and Halog, A. (2016) 'Firm characteristics and its adaptive capacity in response to environmental requirements: an empirical study of Vietnam's textile and garment SMEs', *International Journal of Environment and Sustainability*, Vol. 4, No. 4, pp.1–18.

Paul, S., Das, S., Raul, P. and Bhattacharya, S.S. (2018) 'Vermi-sanitization of toxic silk industry waste employing *Eisenia fetida* and *Eudrilus eugeniae*: substrate compatibility, nutrient enrichment and metal accumulation dynamics', *Bioresource Technology*, Vol. 266, No. 19, pp.267–274.

Rao, P.J.M. (2005) 'Comparative performance of cane sugar industry in seven countries', *Cooperative Sugar*, Vol. 37, No. 1, p.49.

Rong, L., Zhang, C., Jin, D. and Dai, Z. (2017) 'Assessment of the potential utilization of municipal solid waste from a closed irregular landfill', *Journal of Cleaner Production*, Vol. 142, No. 1, pp.413–419.

Sangwan, P., Kaushik, C.P. and Garg, V.K. (2008a) 'Feasibility of utilization of horse dung spiked filter cake in vermicomposters using exotic earthworm *Eisenia foetida*', *Bioresource Technology*, Vol. 99, No. 7, pp.2442–2448.

Sangwan, P., Kaushik, C.P. and Garg, V.K. (2008b) 'Vermiconversion of industrial sludge for recycling the nutrients', *Bioresource Technology*, Vol. 99, No. 18, pp.8699–8704.

Sangwan, P., Kaushik, C.P. and Garg, V.K. (2010) 'Vermicomposting of sugar industry waste (press mud) mixed with cow dung employing an epigeic earthworm *Eisenia fetida*', *Waste Management & Research*, Vol. 28, No. 1, pp.71–75.

Sen, B. and Chandra, T.S. (2007) 'Chemolytic and solid-state spectroscopic evaluation of organic matter transformation during vermicomposting of sugar industry wastes', *Bioresource Technology*, Vol. 98, No. 8, pp.1680–1683.

Sharma, K. and Garg, V.K. (2017) 'Management of food and vegetable processing waste spiked with buffalo waste using earthworms (*Eisenia fetida*)', *Environmental Science and Pollution Research*, Vol. 24, No. 8, pp.7829–7836.

Singh, D. and Suthar, S. (2012a) 'Vermicomposting of herbal pharmaceutical industry waste: earthworm growth, plant-available nutrient and microbial quality of end materials', *Bioresource Technology*, Vol. 112, No. 10, pp.179–185.

Singh, D. and Suthar, S. (2012b) 'Vermicomposting of herbal pharmaceutical industry solid wastes', *Ecological Engineering*, Vol. 39, No. 2, pp.1–6.

Singh, J., Kaur, A., Vig, A.P. and Rup, P.J. (2010) 'Role of *Eisenia fetida* in rapid recycling of nutrients from bio sludge of beverage industry', *Ecotoxicology and Environmental Safety*, Vol. 73, No. 3, pp.430–435.

Subramanian, S., Sivarajan, M. and Saravanapriya, S. (2010) 'Chemical changes during vermicomposting of sago industry solid wastes', *Journal of Hazardous Materials*, Vol. 179, Nos. 1–3, pp.318–322.

Suthar, S., Mutiyar, P.K. and Singh, S. (2012) 'Vermicomposting of milk processing industry sludge spiked with plant wastes', *Bioresource Technology*, Vol. 116, No. 14, pp.214–219.

Suthar, S., Sajwan, P. and Kumar, K. (2014) 'Vermiremediation of heavy metals in wastewater sludge from paper and pulp industry using earthworm *Eisenia fetida*', *Ecotoxicology and Environmental Safety*, Vol. 109, No. 11, pp.177–184.

Yadav, A. and Garg, V.K. (2009) 'Feasibility of nutrient recovery from industrial sludge by vermicomposting technology', *Journal of Hazardous Materials*, Vol. 168, No. 1, pp.262–268.

Yadav, A. and Garg, V.K. (2010) 'Bioconversion of food industry sludge into value-added product (vermicompost) using epigeic earthworm *Eisenia fetida*', *World Review of Science, Technology and Sustainable Development*, Vol. 7, No. 3, pp.225–238.

Yadav, A. and Garg, V.K. (2011) 'Recycling of organic wastes by employing *Eisenia fetida*', *Bioresource Technology*, Vol. 102, No. 3, pp.2874–2880.

Yadav, A. and Garg, V.K. (2013) 'Nutrient recycling from industrial solid wastes and weeds by vermiprocessing using earthworms', *Pedosphere*, Vol. 23, No. 5, pp.668–677.

Yadav, A., Gupta, R. and Garg, V.K. (2013) 'Organic manure production from cow dung and biogas plant slurry by vermicomposting under field conditions', *International Journal of Recycling of Organic Waste in Agriculture*, Vol. 2, No. 1, p.21.

Yadav, A., Suthar, S. and Garg, V.K. (2015) 'Dynamics of microbiological parameters, enzymatic activities and worm biomass production during vermicomposting of effluent treatment plant sludge of bakery industry', *Environmental Science and Pollution Research*, Vol. 22, No. 19, pp.14702–14709.