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Role of bulking agents, process optimization, and different earthworm species in the vermiremediation process of industrial wastes: A review

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Abstract

Rapid industrialization and consumerism have aggravated the generation of industrial waste globally, consequently posing a serious problem related to their treatment, disposal, and management. Industrial wastes or sludges are mainly characterised by undesirable levels of heavy metals, toxic chemicals, and other toxic organic compounds. Deposition of such wastes in the environmental matrices for prolonged periods may result in serious contamination, and the consequent accumulation of these harmful constituents in the ecological food chain. Unavailability of appropriate disposal mechanisms for these sludges is a matter of serious concern that could severely pollute the environment and risk human health. Vermicomposting has emerged as a feasible and environmentally friendly bioremediation technology that could provide a solution to this problem. However, the vermicomposting of industrial sludges requires a better understanding of its inextricable factors to make it a viable process. Thus, the present study was undertaken to provide insights on the influence of different bulking agents and abiotic factors on the vermicomposting process, as well as, the role of different earthworm species in the successful implementation of this process in the bioremediation of industrial waste.

Keywords: abiotic factors; bulking agents; earthworms; industrial wastes; vermicomposting

Abbreviations: AOXs - Adsorbable Organic Halides; EDs - Endocrine Disruptors; EPS -Extracellular Polymeric Substance; MT - Multifunctional Metallothionein; PAHs - Polyaromatic Hydrocarbons; PHCs - Petroleum Hydrocarbons; TPHs - Total Petroleum Hydrocarbons

Introduction

The environmentally nonchalant and linear approach to industrialization because of increasing global population and consumerism has resulted in an increased waste production in the 21st century (Stoeva and Alriksson, 2017; Minelgaitė and Liobikienė, 2019). Recent reports illustrate that industries produce millions of tonnes of wastes every year, and this waste generation is anticipated to increase by three times by 2100 (Krishnan *et al*., 2021). Consequent amassment of environmental contaminants from industrial wastes in marine, freshwater, and terrestrial ecosystems has been a matter of serious concern (Tornero and Hanke, 2016; Wani *et al*., 2022). This has concomitantly aggravated the environmental problems related to industrial waste

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management and disposal (Sandberg *et al*., 2019). In general, industrial wastes are characterized by undesirable levels of heavy metals (Pb, Cd, Cu, Cr, As, Hg, Zn, Mn, and Ni) and other toxic chemicals or compounds (Wang *et al*., 2015; Su *et al*., 2019). Besides heavy metals, organic compounds such as phenols, pyrenes, polyaromatic hydrocarbons (PAHs), petroleum hydrocarbons (PHCs), adsorbable organic halides (AOXs), endocrine disruptors (EDs), etc., constitute other major environmental contaminants (Filali-Meknassi *et al*., 2004; Da Silva *et al*., 2007; Shomar, 2007; Nam *et al*., 2012; Oh *et al*., 2016; Johnson and Affam, 2019). Deposition of large amount of such wastes for longer period may result in percolation of these toxic constituents (toxic metals, phenols, pyrenes, PAHs, PHCs, AOXs, EDs, etc.) into groundwater through soil layers (Świerk *et al*., 2007). Besides groundwater contamination (Brockway and Urie, 1983), other possible consequences attributed to waste deposition include soil contamination and its related plant ecotoxic effects, and spread of harmful pathogens (Manzetti and van der Spoel, 2015). However, dearth of adequate dehydration and disposal mechanism of these wastes warrants effective mitigation measures of these environmental contaminants (Liu *et al*., 2019; Bilal and Iqbal, 2020).

Although several methods have been utilized for industrial wastes treatment, their coverage has been insufficient (Raghunandan *et al*., 2014, 2018; Verma and Kuila, 2019). Techniques such as incineration, oxidation, chemical decomposition, etc., have their own limitations and are largely cost intensive (Zouboulis *et al*., 2019). In addition, the processes of waste incineration, oxidation, chemical decomposition, etc., have detrimental effects on the environment. The major effects on the environment include global warming, smog formation, eutrophication, acidification, formation of other recalcitrant by-products (carboxylic acids, alcohols, aldehydes, etc.), and animal toxicity (Kommineni *et al*., 2000; Yang *et al*., 2012; Sharma *et al*., 2013). Conventional management strategies like land-filling does not actually solve the problem of environmental pollution, but rather contribute to further deposition of harmful contaminants in the environment (Zouboulis *et al*., 2019). In this regard, vermicomposting has emerged as a feasible and environmentally clean bioremediation technology which utilizes the biodegradation potential of earthworms (Bhat *et al*., 2017). Vermicomposting is generally a non-thermophilic decomposition process in which organic residues or wastes are transformed into a valuable finished clean product called vermicompost with the synergistic action of earthworms and mesophilic microorganisms (Bhat *et al*., 2013; Lim *et al*., 2016). Earthworms are capable of expeditious and effectual decomposition as well as remediation of various organic and industrial wastes (Hickman and Reid, 2008). Earthworms secrete an extracellular polymeric substance (EPS) through their skin tissues when put under metal stress, which help them to bind with and accumulate heavy metals (Khan *et al*., 2019). These EPS (a.k.a. exopolymers) are mainly proteins, polysaccharides, humic acids, nucleic acids, lipids, and enzymes (Costa *et al*., 2018). For instance, a recent study demonstrated that an extracellular polymeric substance (EPS) produced by the *Bacillus licheniformis* strain KX657843 isolated from the gut of *Metaphire posthuma* was efficient in the sorption of Cu (II) and Zn (II) (Biswas *et al*., 2020). It can be suggested that EPS producing microorganisms are primarily influenced by the earthworm gut environment (Biswas *et al*., 2019). In addition, multifunctional metallothionein (MT) protein production is stimulated in earthworms and these proteins aid in detoxifying various metal ions (Gruber *et al*., 2000).

The vermicomposting process is dependent on various factors such as the initial C:N ratio, temperature, pH, moisture, light, and nature of the organic waste. Also, these factors influencing the process are inseparably associated with the earthworm species being utilized during the biodegradation process (Lim *et al*., 2016). Earthworms can degrade most organic materials with an initial C/N ratio around 30 (Ndegwa and Thompson, 2000; Lim *et al*., 2016). The bulking agents make the organic wastes more palatable for the survivability of earthworms as well as maintain a conducive milieu for the worms to multiplicate (Adhikari *et al*., 2008). Temperature plays an important function in both composting and vermicomposting process as it affects the microbial as well as the earthworms' activity. As per reports, microbial activity multiplies by two folds per each 10°C increase in temperature and earthworms exhibit efficient activity at mesophilic temperatures ranging from 15-30°C (Rostami *et al*., 2009; Rostami, 2011). The pH of the waste can be a limiting factor affecting the distribution and number of worms as earthworms are very sensitive (Ibrahim *et al*., 2016). Also, low moisture content negatively affect the survival and reproductive rates of earthworms (Wever *et al*., 2001). Availability of light also influences the vermicomposting process as earthworms have a hostility to bright lights. Ultraviolet rays from intense sunlight can cause partial-to-complete paralysis and fatality of earthworms (Ibrahim *et al*., 2016). It is noteworthy to mention that the process of vermicomposting is also dependent on its micro or internal environment (inside the compost pile), for which the process conditions/parameters have to be maintained separately with respect to the above-mentioned factors (Bhattacharya and Kim, 2016; Lim *et al*., 2016; Ganti, 2018).

Although attempts have been made to understand the efficiency of vermicomposting on the biodegradation of different industrial wastes, the potentiality of different types of earthworms in the management of industrial wastes is yet to be fully explored. It is also necessary to understand the influence of various abiotic factors and bulking agents inextricably associated with the process and its process management for a successful implementation of the overall vermi-remediation process. Therefore, the present review was undertaken with the following objectives:

i. Evaluate the influence of bulking agents, and abiotic factors, and different earthworm species on vermicomposting and its process management.
ii. Understand the detoxifying mechanism employed by earthworms.

Vermicomposting: an empirical approach in industrial waste management

Bioconversion of industrial wastes or sludges by earthworms is an effective method as it decreases the toxicity of these wastes and may act as an effective alternative to the traditional composting process and other inexpensive techniques (Ndegwa and Thompson, 2001; Bhat *et al*., 2017).

Importance of bulking agents

Bulking agents are mainly carbon-based particles which add structure to the compost pile and help in controlling the air supply, moisture content, and other vital composting parameters (*e.g.,* C:N ratio, pH, and temperature) (Adhikari *et al*., 2008; Chang and Chen, 2010; Lim *et al*., 2016; Karwal and Kaushik, 2020) (Table 1). Examples of some popular bulking agents include cow dung, poultry waste, rabbit manure, sawdust, rice bran, rice husk, sugarcane trash, grass clippings, biochar, and fruit and vegetable waste (Manish *et al*., 2013). Various bulking agents have mainly shown to induce positive effects on the survivability and reproduction of earthworms during vermicomposting, for instance, Domínguez *et al*. (2000) reported that amendment of paper and carboard mixtures with sewage sludge induced better reproductive rates in *Eisenia andrei* as compared to the control (without bulking agent). Kumar Badhwar *et al*. (2020) demonstrated similar positive results, wherein the amendment of cow dung in the vermicomposting of paper mill sludge and tea waste reported an increased reproducibility rate of *Eisenia fetida*. Studies have also shown that amendment of cow dung and other bulking agents not only supports earthworm biomass and fecundity, but also enhances the quality of final vermicompost (Karmegam *et al*., 2019).

Augmentation of bulking materials with industrial wastes/sludges have been reported to accelerate the vermicomposting process mainly because of maceration and mixing of such carbon-rich agents in the earthworm gut (Domínguez *et al*., 1997). The bulking materials are capable of improving or stabilizing the C:N ratio by providing C and reducing the loss of N by ammonia volatilization, which consequently facilitates the bacterial activity during vermicomposting (Domínguez *et al*., 2000; Rostami, 2011). Bulking agents such as cow dung and sawdust have shown to control the C:N ratio during composting (Singh and Kalamdhad, 2012;

Biruntha *et al*., 2020). Bulking materials such as biogas slurry and wheat straw were observed to decrease the organic C content and increase the available NPK content in the final composted product (Suthar, 2010). Addition of biochar during composting has shown to reduce the loss of nitrogen content (Dias *et al*., 2010). Bulking agents help in maintaining pH at an optimum range of 6-8 during composting (Chang and Chen, 2010). Amendment of sugarcane bagasse during the composting of crude oil showed 100% degradation of total petroleum hydrocarbons (TPHs) (Hamzah *et al*., 2012).

Table 1. Effects of different bulking agents in the composting/vermicomposting process

Sl. No.	Bulking agents	Process	Effects	References
1.	Biochar	Composting	Reduction of nitrogen loss	(Dias *et al*., 2010)
2.	Clinoptilolite and saw dust	Composting	High intake of heavy metals and increase in humic substances	(Zorpas and Loizidou, 2008)
3.	Cotton gin and grape marc	Composting	Control pH and temperature, and enhance compost quality	(Madejón *et al*., 2001)
4.	Cotton waste and maize straw	Composting	Reduce nitrogen loss, enhance nitrogen fixation, and production of stabilized organic matter	(Paredes *et al*., 1996)
5.	Cow dung	Vermicomposting	Increase in worm biomass	(Gajalakshmi *et al*., 2002)
6.	Cow dung	Vermicomposting	Reduction in C:N ratio	(Kaushik and Garg, 2003)
7.	Cow dung	Composting and vermicomposting	Increase in enzymatic activity in earthworms	(Pramanik, 2010)
8.	Cow dung	Vermicomposting	Stabilize pH, reduce heavy metal content, and produce good quality compost	(Garg and Gupta, 2011a)
9.	Cow dung	Vermicomposting	Increase growth and reproductive rate in earthworms	(Kumar Badhwar *et al*., 2020)
10.	Cow dung	Vermicomposting	Reduction in C:N ratio and increase in NPK content	(Biruntha *et al*., 2020)
11.	Cow dung and saw dust	Composting	Control pH, bulk density, and carbon content	(Singh and Kalamdhad, 2012)
12.	Saw dust	Composting	Reduction of polyaromatic hydrocarbons	(Oleszczuk, 2006)
13.	Grape stalk and olive leaf	Composting	Improve aeration, control temperature, regulate C:N ratio, and control pH	(Alburquerque *et al*., 2006)
14.	Onion peel	Composting	Reduction in C:N ratio and production of mature compost	(Abdullah *et al*., 2013)
15.	Press mud	Composting and vermicomposting	Reduction in pH, total organic carbon, C:N ratio, and favours growth and reproduction of earthworms	(Karwal and Kaushik, 2020)
16.	Rice husk	Composting	Control temperature and moisture	(Chang and Chen, 2010)
17.	Rice straw	Composting	Decrease in total organic carbon and organic matter	(Zhu, 2007)
18.	Saw dust	Composting	Control pH, moisture, temperature, bulk density, and aeration	(Adhikari *et al*., 2008)

19.	Star grass and sugarcane bagasse	Composting	Improve pH, moisture, and total organic carbon	(Oviedo-Ocaña *et al*., 2015)
20.	Sugarcane trash	Composting	Control pH, moisture, and carbon content	(Goyal *et al*., 2005)
21.	Waste paper and plant residue	Composting	Decrease in organic matter, intake of trace metals, decrease in organic C and C:N ratio	(Tian *et al*., 2012)

Composting of industrial sludges with amendment of saw dust reported reduction of polyaromatic hydrocarbons (PAHs) (Oleszczuk, 2006). Studies have shown that adding clinoptilolite (a natural zeolite) in the initial mixture helps in taking up of heavy metals, which warrants its efficiency as a bulking agent in the metal remediation of industrial sludges (Zorpas and Loizidou, 2008). Such favourable conditions induced by bulking agents promote the survival of earthworms (Manish *et al*., 2013; Ibrahim *et al*., 2016).

Influence of climatic factors

Apart from the influence of different bulking agents, abiotic factors like temperature, moisture/humidity, and light also play an important role in the quality of compost, as well as, the growth and reproductivity of earthworms (Gopal *et al*., 2004; Tang *et al*., 2007; Garg and Gupta, 2011b; Zhou *et al*., 2021) (Table 2).

Table 2. Influence of abiotic factors on composting/vermicomposting process

Abiotic factors	Process	Effects	References
Temperature	Composting	Increase in microbial population and efficiency of the process at high temperature	(Chinakwe *et al*., 2019)
	Composting	Efficient degradation of tetracyclines and rapid composting at 70 °C	(Yu *et al*., 2019)
	Composting	Higher TOC ratio and reduction in C:N ratio at high temperature (46 °C).	(Kianirad *et al*., 2010)
	Composting	Higher decomposition activity of microbes and mass reduction of organic matter at mesophilic temperature (35 °C-37 °C)	(Tang *et al*., 2007)
	Composting	High protein degradation and high bacterial activity at 54 °C	(Miyatake and Iwabuchi, 2005)
	Composting	Higher degradation of organic matter and conversion of volatile matter at 60 °C	(Nakasaki *et al*., 1985)
	Vermicomposting	High enzymatic activity and increase in total nitrogen, total phosphorus, and total potassium content at 30 °C	(Zhou *et al*., 2021)
	Vermicomposting	Decrease in organic matter, high electrical conductivity, and high nitrate content at 25 °C.	(Zhang *et al*., 2020)
	Vermicomposting	High organic matter degradation, reduction in C:N ratio, increase in total Kjeldahl nitrogen in winter (low temperature)	(Garg and Gupta, 2011b)
	Vermicomposting	Better growth of earthworms and good quality compost in temperature range 15 °C-25 °C	(Rostami *et al*., 2009)
	Vermicomposting	Better vermicompost turnover, number of earthworms (*Eudrilus* sp.) and worm biomass at low temperature	(Gopal *et al*., 2004)

	Vermicomposting	Efficient life activity of *Eudrilus eugeniae* in temperature range 25 °C-28 °C	(Shagoti *et al*., 2001)
	Vermicomposting	Efficient activity and reproductivity capacity of *Eudrilus eugeniae* at low temperature	(Amoji *et al*., 1999)
Moisture/ Humidity	Composting	Decrease in total organic matter, increase in total nitrogen and better compost quality at 53% moisture content	(Li *et al*., 2021)
	Composting	Efficient process activity at initial moisture content of 55-70%	(Yeh *et al*., 2020)
	Composting	High organic matter degradation at 70-75% initial moisture content	(Makan *et al*., 2013)
	Composting	Better stability and maturity of the compost at 65-75% moisture content	(Guo *et al*., 2012)
	Composting	High microbial activity at high moisture content (≥ 50%)	(Liang *et al*., 2003)
	Vermicomposting	High crude fibre degradation and increase in crude protein at 70% moisture content	(Hossen *et al*., 2022)
	Vermicomposting	Better growth of earthworms and good quality compost in moisture content regime 65-75%	(Rostami *et al*., 2009)
	Vermicomposting	Higher reduction in C:N ratio, decomposition rate, and kinetic reaction rate at 75 ± 5% moisture content	(Palsania *et al*., 2008)
	Vermicomposting	Better vermicompost turnover, number of earthworms (*Eudrilus* sp.) and worm biomass at high relative humidity	(Gopal *et al*., 2004)
Light	Vermicomposting	Increase in earthworms' photophobic movement with increase in light intensity	(Lin *et al*., 2018)
	Vermicomposting	Higher cast productivity rate of *Hyperiodrilus africanus* in red light colour and least emigration rate in dark light colour	(Owa *et al*., 2008)
	Vermicomposting	Reduced growth rate and reproductive rate of *Eisenia fetida* in exposure to high frequency light (UV rays)	(Hamman *et al*., 2003)

The investigation on the influence of temperature on vermicomposting showed that earthworms' gut enzymes exhibited higher activity at an optimum temperature of 30 °C. Consequent increment in total NPK was also observed at similar temperature (Zhou *et al*., 2021). Conversely, Zhang *et al*. (2020) reported that an optimum temperature of 25 °C is essential for better organic matter degradation, whereas increasing the temperature slightly accelerated the rate of decomposition, mineralization, and nitrification. Microbes identified in a compost pile (mainly *Proteo-bacteria* and fungi) had greater decomposition activity at mesophilic temperatures (35 °C-37 °C) (Tang *et al*., 2007). The effectiveness of vermicomposting also depends on seasons. It was observed that organic matter degradation by *Eisenia fetida* was higher in the winter as compared to the summer. Reports also suggested that *Eudrilus eugeniae* showed efficient activity and reproductive capacity during the colder seasons (Amoji *et al*., 1999). Gopal *et al*. (2004) investigated the influence of prevailing weather conditions on the growth and biomass of *Eudrilus* sp. and the produced vermicompost. It was observed that the vermicompost turnover, number of earthworms, and worm biomass were negatively corelated to atmospheric temperature. Rostami *et al*. (2009) demonstrated that temperatures maintained in a range of 15 °C-25 °C was optimum for the growth of earthworms as well as the decomposition process. Shagoti *et al*. (2001) reported that *E. eugeniae* demonstrated efficient life activity in optimum temperatures between 25 °C and 28 °C. A pile temperature below 10 °C might induce stress on the earthworms and result in their mortality.

Likewise, a significant increase in temperature might reduce the activity of the earthworms, resulting in reduced reproductive rate (Ganti, 2018). Hence, temperature should be within the earthworms' tolerance capacity to facilitate biodegradation of sludges (Bhattacharya and Kim, 2016) (Figure 1).

Liang *et al*. (2003) investigated the effect of moisture content on the compost microbial activity during the biodeterioration of sludges. Hossen *et al*. (2022) found that an initial moisture content of 70% was suitable for an efficient vermicomposting. Another study reported the influence of moisture content variation on the kinetic reaction rate of vermicomposting. It was observed that rate of vermicomposting and kinetic reaction rate was maximum at 75 ± 5% moisture content (Palsania *et al*., 2008). Yeh *et al*. (2020) reported that an initial moisture regime of 55-70% was more suitable for an effective composting of the wastes. Guo *et al*. (2012) reported that moisture content in the regime of 65-75% was optimum for obtaining a stable and mature compost. Makan *et al*. (2013) also reported that an initial moisture content of 70-75% resulted in a high organic matter degradation during composting. Li *et al*. (2021) demonstrated that an initial moisture content of 53% resulted in a considerable decrease in total organic matter and further facilitated in production of good quality compost. The right amount of moisture can be maintained by employing coarse materials in the compost pile which can absorb oxygen (Ganti, 2018). An optimum moisture content in the regime of 40-55% inside the pile was suitable for vermicomposting of different wastes (Das *et al*., 2020) (Figure 1). Composting of organic wastes requires a moisture content of 60-70% for successful results.

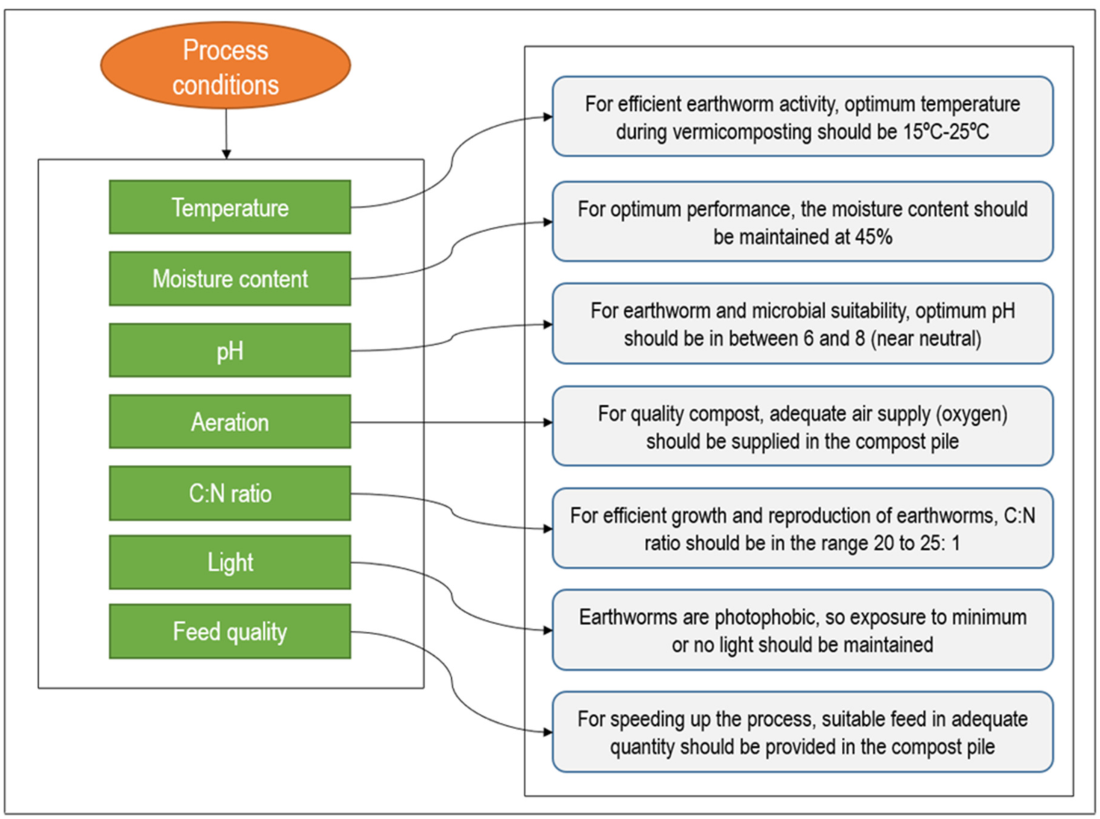

Figure 1. Process conditions maintained during vermicomposting process (modified from: (Bolong and Saad, 2020))

Earthworms are generally photo-sensitive to different light intensity and colour (Lin *et al*., 2018). It was reported that exposure of *E. fetida* to ultra-violet radiations (high frequency light) resulted in a reduced growth rate and reproductive rate in the species and it significantly decreased cocoon fertility rate by 70% (Hamman *et al.*, 2003). Additionally, the effect of light colour on the cast productivity as well as the emigration rate of *Hyperiodrilus africanus* was investigated. The results showed that red light colour was the most suitable for cast productivity followed by blue, green, dark, and white. Also, the rate of emigration was least in dark light colour indicating the preference of this earthworm species for that particular colour (Owa *et al.*, 2008). Lin *et al.* (2018) investigated the effect of different monochromatic lights (white light, yellow light, green light, red light, and incandescent light) and light intensity (10 to 270 lx) on the photophobic reaction of earthworms and found that higher light intensity (270 lx) substantially affected the movement of earthworms away from the light. The results also found that red light exerted the weakest photophobic movement in earthworms. From the results, it can be inferred that exposure to high intensity light and different colours of light can considerably affect the movement of earthworms which consequently might affect the vermicomposting process of sludges and prolong its time period.

Process management

During vermicomposting, the process conditions or control measures inside the compost pile are also to be monitored to achieve efficient earthworm activity (Gurav and Pathade, 2011; Manyuchi and Phiri, 2013). Some of the process conditions which are maintained or monitored inside the compost pile include C:N ratio, pH, aeration, churning, pre-treatment etc. (Raut *et al.*, 2008; Getahun *et al.*, 2012; Manyuchi and Phiri, 2013; Das *et al.*, 2020) (Figure 1).

C:N ratio has to be in an appropriate balance to facilitate better degradation by enhancing the microbial activity during the process (Chen *et al.*, 2011). To enhance industrial sludges with low initial C:N ratio, bulking materials with high C:N ratio is often employed (Zhang and Sun, 2016). Ndegwa and Thompson (2000) reported that C:N ratio = 25:1 is optimum for vermicomposting of biosolids. Similarly, Biruntha *et al.* (2020) tested varied feedstocks (C:N ratio range 23 to 70) in an *E. eugenia* based vermicomposting system and found that C:N ratio in the range of 23-30 is adequate for earthworm proliferation and waste degradation. In this regard, vermicomposting of sludges is a scalable process as a lot of bulking agents with wide C:N ratios have often been utilized during the process (Manish *et al.*, 2013; Das *et al.*, 2020).

Most wastes result in an increase of acidic content of the compost pile during vermicomposting, which consequently affects the survival of earthworms (Katiyar *et al.*, 2017). However, earthworms have the ability to maintain the pH by neutralizing both acidic and alkaline feedstocks by producing alkaline exudates and organic acids respectively (Goswami *et al.*, 2014). Singh *et al.* (2005) reported that a high acidic initial substrate pH was unfavourable for vermicomposting, whereas initial substrate pH close to neutral favoured the most for waste stabilization. Amendment of bulking materials helps in maintaining a near neutral pH inside the compost pile (Adhikari *et al.*, 2008; Chang and Chen, 2010).

Maintaining proper air circulation in compost piles is a prerequisite for achieving an enhanced biodegradation rate (Das *et al.*, 2020). In a bench scale experiment, it was observed that augmenting air for a time period of 4-6 hours at a flow rate of 0.62 L/min per kg was ideal for vermicomposting (Palaniappan *et al.*, 2017). Earthworms also maintain themselves a proper aeration in vermibeds by regulating their movement through it (Kaur, 2020). In this regard, bedding helps in maintaining a proper amount of oxygen during the process (Ganti, 2018). Selection of bedding materials plays a crucial role in the vermicomposting process. Besides maintaining optimum oxygen levels, bedding materials provide protection from extremes in temperature, as well as, a consistency in moisture content (Munroe, 2004). They also affect the growth and fecundity of earthworms during vermicomposting, for instance, Abd Manaf *et al.* (2009) studied the influence of two bedding materials (saw dust and newspaper) using biological parameters such as growth rate, number of worms, number of cocoons, and worm biomass. The results demonstrated that sawdust bedding was better for cocoon production and number of earthworms, while newspaper bedding was better for earthworm biomass production and growth rate.

For maintaining better aeration and transfer of materials in the vermibeds, churning (turning of compost pile) is a common practice which is to be followed. Churning influences the pile thermodynamics and also assist earthworm movement (Getahun *et al.*, 2012) (Figure 2). Abdoli *et al.* (2019) compared the composting efficiency in a static and frequently churned pile and found good microbial biomass and higher earthworm cocoon count in the latter. It also facilitates good porosity and reduces compaction in the vermibeds which is very essential for earthworm growth and proliferation (Bhattacharya and Kim, 2016).

Pre-treatment of sludges in vermicomposting can also influence the duration of the process, survival of earthworms, and nutrient availability. Pre-treatment reduces the process duration and eliminates the harmful pathogens (Ganti, 2018) (Figure 2). The conductivity of the sludges very much affects the process of vermicomposting as earthworms are known to be very sensitive to high conductivity (Gunadi *et al.*, 2002). Thus, sludges or waste materials containing higher salt content should be leached to reduce the salt content. This is mainly achieved by watering the sludges for some period of time during the pre-treatment phase (Kaur, 2020). Singh *et al.* (2021) observed that cellulolytic pre-treatment significantly lessened the earthworm incubation time and reduced C content but increased N availability in the waste. Alshehrei and Ameen (2021) reviewed the usage of chemical pre-treatment in municipal solid waste vermicomposting. Other pre-treatment options like microwave and thermal methods are also possible prior vermicomposting (Amiri *et al.*, 2017; Tayeh *et al.*, 2020).

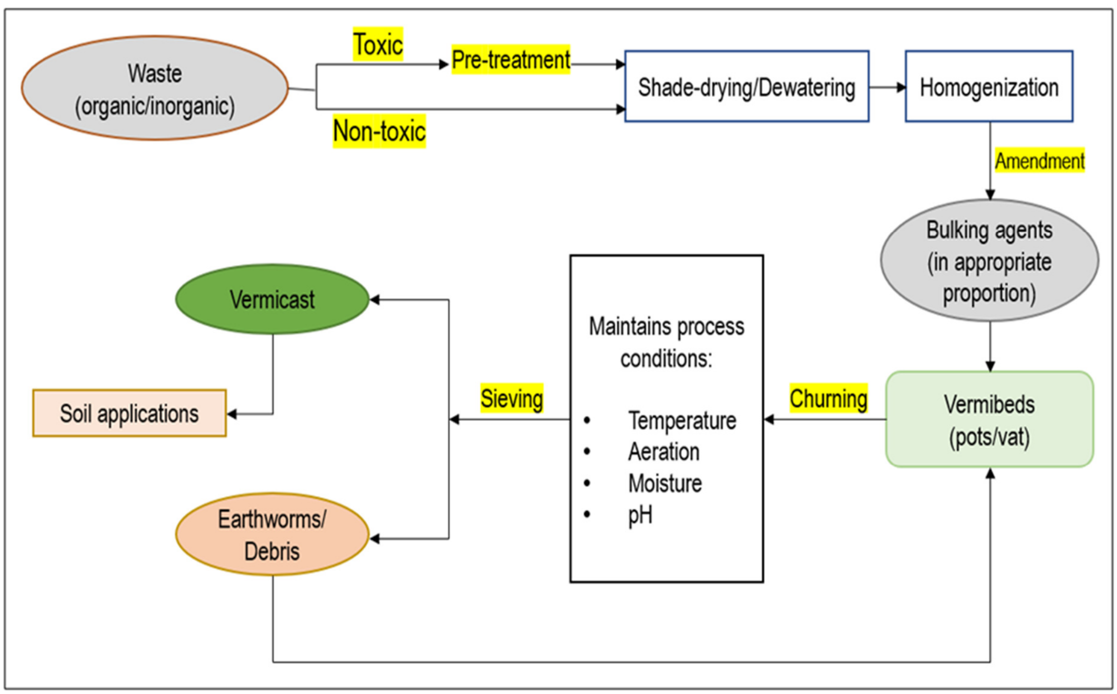

Figure 2. Flow chart illustrating the process of vermicomposting of sludges

Role of different earthworm species in vermiremediation

Often regarded as the intestines of Earth, earthworms play an important role in maintaining soil fertility and in the degradation of wastes (Martin, 1976). Earthworms are mainly categorized into three types depending on the portion of the soil profile that they inhabit, *viz.*, epigeic, endogeic, and anecic (Domínguez, 2018). With regards to vermicomposting, epigeic earthworms are mostly employed in the decomposition process followed by anecic earthworms (Table 3). However, the role of endogeic earthworms in soil organic matter dynamics cannot be overlooked (Das *et al*., 2020). Generally, earthworms play two very important roles in vermicomposting, *i.e*., 1) degradation of wastes and 2) production of quality vermicompost (Yadav and, Garg 2013). In this regard, the incorporation and influence of monoculture (use of one species) and polyculture (use of more than one species) techniques in vermicomposting have also been studied (Khwairakpam and Bhargava, 2010). The results of Khwairakpam and Bhargava (2010) demonstrated that the quality and stability of the produced vermicompost from polyculture technique were better than the vermicompost produced from monoculture technique. Also, the overall reduction in pH, total organic carbon, and coliforms was higher in the polyculture reactors. Similar results were reported by Hussain *et al*. (2018) who compared the efficiency of kitchen waste vermicomposting by single species (*Eisenia fetida/Eudrilus eugeniae/Perionyx excavatus*) and three in combination. They found higher compost maturity, compost quality, microbial enrichment, and nutrient contents in the vermicompost prepared by polyculture technique.

Epigeic earthworms

Epigeic earthworms are mainly surface dwellers and live in the organic horizon and on or near the soil surface (Domínguez, 2018). They mainly feed on fresh organic matter found in forest litter, litter mound, vegetable and animal debris, etc. (Aira *et al*., 2008; Domínguez 2018). They exhibit high metabolism and reproductive rates which help them to adapt and survive in changing environmental conditions (Domínguez, 2018). These earthworms play a very important role in degradation of organic matter and enhances the rate of decomposition as well as nutrient turnover (Gomez-Brandon *et al*., 2011). The influence of epigeic earthworms on soil microbiota is widely varying as they can instigate either an increase or a decrease in microbial biomass (Medina-Sauza *et al*., 2019).

When it comes to vermicomposting of sludges, epigeic species *E. fetida* have been employed extensively (Domínguez, 2018). Apart from this species, *E. eugeniae* and *Perionyx excavatus* have also been utilized in the vermicomposting process (Gajalakshmi *et al*., 2001; Suthar, 2006; Ravindran *et al*., 2015). Other lesser utilized epigeic earthworms include species such as *Dichogaster bolaui* (epi-endogeic species) and *Perionyx simlaensis* (Bhardwaj and Sharma, 2015). Vermicomposting of wastes employing *E. fetida* recorded a significant decrease in pH, organic carbon, C:N ratio, total K and an increase in total N, available P, total Ca, and Mg. Also, heavy metals such as such as Fe, Mn, Zn, Cu, Cr, and Ni in the final vermicompost material were under the permissible levels (Ahmed and Deka, 2022). Reduction of C:N ratio and humification index was reported during the vermicomposting of sludges by *E. fetida* (Boruah *et al*., 2019). More studies on the vermicomposting potential of *E. fetida* for different sludges and other organic substances have been reported (Garg and Kaushik, 2005; Singh *et al*., 2010; Hait and Tare, 2012; Bhat *et al*., 2013; Hanc and Chadimova, 2014; Bhat *et al*., 2016; Busato *et al*., 2016; Cunha *et al*., 2016; Huang *et al*., 2016; Malińska *et al*., 2016; Mupambwa *et al*., 2016; Xie *et al*., 2016; Ravindran and Mnkeni, 2017).

Reports have shown that *Eisenia andrei* could successfully reduce harmful pathogens such as *Escherichia coli* and *Salmonella* spp. during the vermicomposting of organic wastes (Procházková *et al*., 2018). Vermicomposting potential of dairy sludge and paper mill sludge by *E. andrei* has been investigated (Elvira et al. 1998). Vermicomposting of lignocellulosic wastes by *E. eugeniae* showed reduction of C:N ratio in the final vermicompost (Pandit *et al*., 2020). Pressmud vermicomposted by *E. eugeniae* showed a decrease in total organic carbon, C:N ratio, and C:P ratio in the vermicompost (Balachandar *et al*., 2020). Various other investigations on the efficiency of *E. eugeniae* in vermicomposting of sludges/wastes have also been reported (Lalander *et al*., 2015; Ravindran *et a*l., 2016; Taeporamaysamai and Ratanatamskul, 2016; Soobhany *et al*., 2017; Biruntha *et al*., 2020).

Epigeic species *P. excavatus* has also shown heavy metal accumulation potential for metals such as Cd, Cu, Pb, and Cr during the vermicomposting of sludges. The final produced vermicompost showed a decrease in total organic carbon, C:N ratio, and C:P ratio and an increase in total NPK content *(Yuvaraj et al*., 2018). More studies on the efficiency of *P. excavatus* in vermicomposting have been reported (Suthar, 2006; Ananthavalli *et al*. 2019). The potential of *Lumbricus rubellus* (epigeic) in vermicomposting of sludges has also been reported (Azizi et al. 2013; Shah et al. 2015) Vermicomposting of industrial sludges using consortia of different earthworm species has also been investigated. Yuvaraj *et al*. (2020) investigated the efficiency of vermicomposting of textile sludge using two earthworm species *E. eugeniae* and *P. excavatus* and reported good heavy metal accumulation by the earthworms and a significant increase in NPK content in the final product.

Endogeic earthworms

Endogeic earthworms, characterized by little pigmentation, low reproductive rates and long life cycles, live in deeper section of the soil profile and feed mainly on soils enriched with organic matter (Domínguez, 2018). With respect to disturbed soil conditions, they prove themselves to be highly resistant and can survive unfavourable conditions like drought and food shortage (Jouquet *et al*., 2010; Domínguez, 2018; Das *et al*., 2020). These earthworms are capable of ingesting a large amount of soil and assimilating greater soil organic matter (Bernard et al. 2012). They are highly diverse as they are found in urban soils to temperate soils (Schlaghamerský and Pižl, 2009; Glasstetter, 2012).

Endogeic earthworms are not extensively used in vermicomposting as compared to the epigeic and anecic earthworms. One possible reason could be that these earthworms are not detrivores for which they do not feed on litter or debris and mostly prefer to live in deeper soil profiles (Das *et al*., 2020). However, a few studies on the vermicomposting potential of endogeic earthworms have been carried out. For instance, Das *et al*. (2016) investigated vermicomposting of sludges by endogeic species *Metaphire posthuma*. The results showed that there was increment in total NPK availability, stable humic acid C formation, fulvic acid C, and microbial biomass C in the final vermicompost produced. A decrease in total organic carbon and pH was also recorded. Sahariah *et al*. (2015) also investigated the efficiency of *M. posthuma* in vermicomposting of municipal sludges. The results showed that this species was potentially capable of accumulating heavy metals such as Pb, Zn, Mn, and Cu. Moreover, the final vermicompost product recorded an increase in total N and available P, K, and Fe content. Enhancement in humification rate and fulvic/humic acid C was also reported. Reports have also shown the vermicomposting potential of the endogeic species *Pheretima elongata* (Munnoli *et al*., 2000).

Although other endogeic earthworm species have not been investigated extensively in vermicomposting, but they are equally resourceful when it comes to providing other services such as maintaining soil characteristics and in growth of different plant species (Doube *et al*., 1997; Hallam *et al*., 2021). For instance, Doube *et al*. (1997) investigated the ability of two endogeic species *Aporrectodea trapezoides* and *Aporrectodea rosea* in the growth of three crop plants - wheat, barley and faba beans. Bernard *et al*. (2012) reported that *Pontoscolex corethrurus* was capable of inducing a priming effect (stimulation of mineralization of soil organic matter) and subsequently enhancing soil respiration. Another species *Allolobophora chlorotica* has shown accumulation potential for the cationic analogue strontium (Sr) (Morgan et al. 2002). Van Vliet *et al*. (2006) reported that *A. chlorotica* and *Aporrectodea caliginosa* could efficiently accumulate heavy metals such as arsenic, cadmium, and zinc. Eck *et al*. (2015) investigated the priming effect of *A. caliginosa* on young rhizodeposits and old soil organic matter and found that this species induced strong priming effect on old soil organic matter.

Anecic earthworms

Anecic earthworms mainly live in the vertical galleries of the soil profile and feed on soil as well as litter and partially mineralized organic matter (Domínguez, 2018; Das *et al*., 2020). They mainly come out to the surface at night to feed on surface litter and other partially decomposed matter (Kiyasudeen *et al*., 2015). Anecic earthworms play a crucial role in accelerating the pedological processes by enhancing decomposition of soil organic matter, nutrient cycling, and soil formation (Kiyasudeen *et al*., 2015; Gavinelli *et al*., 2018). Bottinelli *et al*. (2021) demonstrated that anecic earthworms (*Amynthas adexilis*) could induce soil generation to counteract the effects of soil erosion. The influence of anecic species *Lampito mauritii* on soil enzymatic activity in cadmium-amended soils has also been studied, wherein this species by accumulating Cd in their gut reduced the Cd-induced stress in microorganisms resulting in an increased microbial enzymatic activity (Sivakumar *et al*., 2015). Anecic earthworms, even if not extensively like epigeic earthworms, have been utilized in vermicomposting (Das *et al*., 2020). Rajadurai *et al*. (2022) investigated the vermiremediation efficiency *L. mauritii* on engine oil contaminated soils. The results showed a total reduction of polyaromatic hydrocarbons (PAHs) and total petroleum hydrocarbons (TPHs) by 68.6% and 34.3% respectively. Also, the vermiremediated soils recorded an elevation in the NPK content. Prashija *et al*. (2017) recorded decrease in pH, organic carbon, C:N ratio, C:P ratio, lignin, cellulose, hemicellulose, and phenol content and increase in NPK and humic content in the final vermicompost produced from lignocellulosic wastes by *L. mauritii*. Goswami *et al*. (2014) reported efficient accumulation of heavy metals such as Mn, Zn, Cu, and As by *L. mauritii* during the vermicomposting of tea factory coal ash. The results also observed reduction of total organic C and pH to neutrality and increase in total N in the final vermicompost. Maity *et al*. (2008) found that *L. mauritii* was capable of immobilizing Pb^{2+} and Zn^{2+} in metal treated soils. The final vermicast showed reduction of C:N ratio as a result of reduction of organic C and nitrogen fixation. Available P and K content also increased as a result of worm activity. Banu *et al*. (2008) investigated the vermicomposting sludges by *L. mauritii* and found that organic carbon content decreased and total nitrogen increased in the final product. Tripathi and Bhardwaj (2004) studied the decomposition potential of *L. mauritii* and reported an increase in organic carbon, nitrogen, phosphorus, and potassium content by 14%, 102%, 33% and 42% respectively and decrease in C:N and C:P ratios by 43% and 14% respectively. Gajalakshmi *et al*. (2001) also investigated the vermicomposting potential of the anecic species *Drawida willsi*.

Table 3. Role of different earthworms in vermicomposting of organic and inorganic wastes

Category	Earthworm species	Wastes (organic/inorganic)	Effects	References
Epigeic	*Eisenia fetida*	Patchouli bagasse from oil industry	Decrease in organic C, C:N ratio, C:P ratio and total K, increase in total P and Ca, and heavy metal accumulation	(Ahmed and Deka, 2022)
	Eisenia fetida	Spent drilling fluid from Nature-gas industry	Decrease in total organic C, C:N ratio, and increase in total NPK content	(Wang *et al*., 2021)
	Eisenia fetida	Paper mill sludge + citronella bagasse	Reduction of C:N ratio and humification index	(Boruah *et al*., 2019)
	Eisenia fetida	Spent grains from brewery	Decrease in total organic C, and increase in total N and total humic substances	(Saba *et al*., 2019)
	Eisenia fetida	Sewage sludge	-	(Malińska *et al*., 2016)
	Eisenia fetida	Fruits and vegetable wastes	Decrease in total organic C and increase in total N	(Huang *et al*., 2016)
	Eisenia fetida	Tannery sludge	-	(Cunha *et al*., 2016)
	Eisenia fetida	Filter cake	Decrease in total organic C and total N	(Busato *et al*., 2016)

	Eisenia fetida	Wastewater sludge	Decrease in pH value, total organic C, and C:N ratio, and increase in total available P	(Xie *et al*., 2016)
	Eisenia fetida	Fly ash	Decrease in C:N ratio	(Mupambwa *et al*., 2016)
	Eisenia fetida	Press mud	Decrease in total organic C, C:N ratio, and K content, and increase in N, P, and Na content	(Bhat *et al*., 2016)
	Eisenia fetida	Apple pomace wastes	Increase in available nutrients such as N, P, K, and Mg	(Hanc and Chadimova, 2014)
	Eisenia fetida	Dyeing sludge	Decrease in electrical conductivity, C:N ratio, organic C, and K content, and increase in N, P, and Na content	(Bhat *et al*., 2013)
	Eisenia fetida	Sewage sludge	Increase in total N and P content, and decrease in metal content	(Hait and Tare, 2012)
	Eisenia fetida	Beverage sludge	Decrease in electrical conductivity, organic C, and K content, and increase in N, P, and Na content	(Singh *et al*., 2010)
	Eisenia fetida	Textile sludge	Reduction in C:N ratio and increase in N and P content.	(Garg and Kaushik, 2005)
	Eisenia andrei	Apple pomace wastes	Reduction of pathogenic *Enterococci* and *E. coli*	(Procházková *et al*., 2018)
	Eisenia andrei	Sewage sludge and kitchen wastes	-	(Hanc and Dreslova, 2016)
	Eisenia andrei	Dairy sludge and paper mill sludge	Increase in N and P content, and low levels of heavy metals	(Elvira *et al*., 1998)
	Eudrilus eugeniae	Coir pith	Decrease in organic matter, total organic C, C:N ratio, C:P ratio and total phenolic content, and increase in electrical conductivity, total NPK and Ca content	(Jayakumar *et al*., 2022)
	Eudrilus eugeniae	Lignocellulosic organic wastes	Stable C:N ratio (15:1)	(Pandit *et al*., 2020)
	Eudrilus eugeniae	Pressmud	Decrease in pH, total organic carbon, C:N ratio, water-soluble organic C and C:P ratios, and increase in NPK content and microbial population	(Balachandar *et al*., 2020)
	Eudrilus eugeniae	Biowastes	Decrease inorganic matter content, total organic C, lignin, cellulose, C:N ratio and C:P ratio, and increase in NPK content	(Biruntha *et al*., 2020)
	Eudrilus eugeniae	Municipal solid waste	Decrease in C:N ratio	(Soobhany *et al*., 2017)
	Eudrilus eugeniae	Fermented tannery waste	Reduction in heavy metals, total organic C, and an increase in total Kjeldahl N	(Ravindran *et al*., 2016)
	Eudrilus eugeniae	Kitchen waste	Decrease in organic matter and organic C, and increase in electrical conductivity and total N, P, and K content	(Taeporamaysamai and Ratanatamskul, 2016)
	Eudrilus eugeniae	Food waste	Increase in total N and decrease in total K	(Lalander *et al*., 2015)

	Eudrilus eugeniae	Tannery waste	Decrease in total organic C and C:N ratio	(Ravindran *et al*., 2015)
	Perionyx excavatus	Seaweed	Decrease in organic C and increase in NPK content	(Ananthavalli *et al*., 2019)
	Perionyx excavatus	Paper mill sludge	Decrease in pH, total organic C, C:N ratio and C:P ratio, and increase in electrical conductivity, total N, total P and total K	(Yuvaraj *et al*., 2018)
	Perionyx excavatus	Guar gum industry waste	Decrease in organic C and increase in total N and P content	(Suthar, 2006)
	Perionyx simlaensis	Organic waste	Decrease in C:N ratio	(Bhardwaj and Sharma, 2015)
	Lumbricus rubellus	Sugarcane industry waste	Increase in essential nutrients like N, P, K, Ca, and Na	(Shah *et al*., 2015)
	Lumbricus rubellus	Sewage sludge	Decrease in heavy metals Cr, Cd and Pb	(Azizi *et al*., 2013)
	Eudrilus eugeniae + *Perionyx excavatus*	Textile mill wastewater sludge	Decrease in heavy metal content and increase in NPK content	(Yuvaraj *et al*., 2020)
Epi-endogeic Endogeic	*Dichogaster bolaui*	Organic waste	Decrease in C:N ratio	(Bhardwaj and Sharma, 2015)
	Metaphire posthuma	Jute mill waste	Decrease in total organic C and pH, and increase in N, P, and K availability	(Das *et al*., 2016)
	Metaphire posthuma	Municipal solid waste	Reduction in pH and total organic C and increase in total N and availability of P, K, and Fe	(Sahariah *et al*., 2015)
	Metaphire posthuma	Organic waste	Decrease in C:N ratio	(Bhardwaj and Sharma, 2015)
	Pheretima elongata	Potato peels	-	(Munnoli *et al*., 2000)
Anecic	*Lampito mauritii*	Lignocellulosic organic waste	Decrease in pH, organic C, C:N ratio, C:P ratio, lignin, cellulose, hemicellulose and phenol content, and increase in N, P, K content, dehydrogenase and humic acid	(Prashija *et al*., 2017)
	Lampito mauritii	Tea factory coal ash	Decrease in total organic C and increase in total N content and heavy metal accumulation	(Goswami *et al*., 2014)
	Lampito mauritii	Metal treated soil	Decrease in C:N ratio and increase in availability of P and K	(Maity *et al*., 2008)
	Lampito mauritii	Sago sludge	Decrease in organic C and increase in N and P content	(Banu *et al*., 2008)
	Lampito mauritii	Kitchen waste	Decrease in C:N ratio and C:P ratio and increase in N, P and K content	(Tripathi and Bhardwaj, 2004)

Underlying mechanism of earthworms in waste detoxification process

Earthworms are capable of crushing organic materials into smaller fragments with the help of their gut mediated processes. The gut extends from the mouth to the anus and consists of different sections like muscular pharynx, oesophagus, intestines, and associated digestive glands (Figure 3).

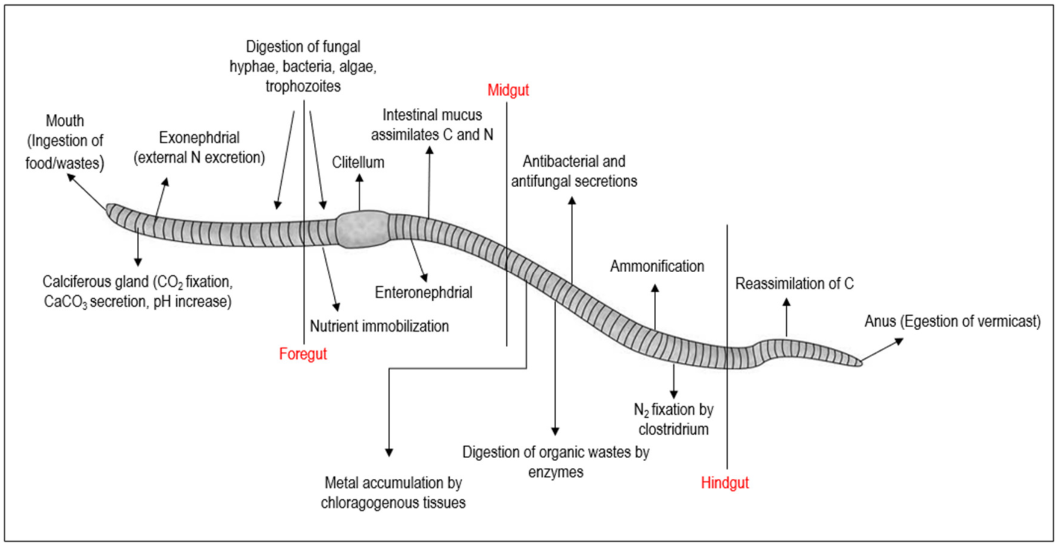

Figure 3. Internal mechanism of earthworms in organic material decomposition and metal uptake. The font in red colour designates the three major sections in an earthworm gut (foregut-frontal region; midgut-middle region, and hindgut-posterior region) (modified from: (Lemtiri *et al*., 2014))

The gut usually consists of mucus and microbes such as bacteria, protozoa, and fungi which contribute to degradation of organic matter at accelerated rates (Munnoli *et al*., 2010). The influential grinding mechanism of the earthworm's gut is brought about by the strong ligands produced in the gut and peristalsis (contraction and relaxation) which helps in the movement of food (Carpenter *et al*., 2007). It is observed that the gut provides a suitable environment for the incubation of microbial colonies (Edwards and Lofty, 1977). The gut microbiota degrade the organic matter through secretion of hydrolytic enzymes (Swati and Hait, 2017). Several digestive enzymes such as protease, invertase, amylase, lipase, cellulase, chitinase, etc., present in the alimentary canal help in the process of decomposition (Edwards, 1988b). Such digestive enzymes decompose organic matter constituents such as cellulose, hemicellulose, lignin, and proteins (Garcia *et al*., 1992; Lemtiri *et al*., 2014).

The intestinal mucus of earthworms mainly consists of gluco-proteins and other glucosidic and proteic molecules (Morris, 1985). The nitrogenous compounds present in the mucus significantly enhances the gut microbial activity (Zhang *et al*., 2000; Lemtiri *et al*., 2014). The chemical changes of the ingested organic matter are brought about by enzymatic digestion (Sharma, 1994). As a consequence of these processes, aromatic protein compounds in the organic matter decrease, whereas humic acid-like and fulvic acid-like substances increase (Fernández-Gómez *et al*., 2015). Ingestion of organic materials by earthworms increases the microbial count in the gut up to 1000-fold (Edwards, 1988a). These microbe species are primarily the N-fixing and decomposer type which are excreted out with nutrients as vermicasts (Singleton *et al*., 2003). Reports suggested that the neutral pH and moist conditions of the foregut of earthworms promoted the growth of microbes capable of digesting cellulose (Lavelle and Gilot, 1994). Singleton *et al*. (2003) reported the presence of hydrocarbon degrading bacteria such as *Pseudomonas alcaligenes* and *Acidobacterium* in the gut of earthworms. Hussain *et al*. (2016) identified and isolated N-fixing and P-solubilizing bacterial strains of the genus *Bacillus*, *Serratia*, *Burkholderia*, and *Kluyvera* from the gut of earthworms.

Earthworms enhance the process of mineralization by mixing the fragmented organic matter with mineral particles and microorganisms (Parmelee, 1998). Higher mineralization in the produced vermicasts could be attributed to higher microbial activity and a higher concentration of labile compounds such as soluble carbon and lignin (Coq *et al*., 2007). Even in the absence of sufficient gut enzymes, they are capable of digesting organic matter by stimulating soil microbes (Khomyakov *et al*., 2007; Nechitaylo *et al*., 2010; Fujii *et al*., 2012). Primarily, earthworms and microbes stay in a mutualism, wherein earthworms affect the diversity and metabolic activity of microbes and microbes constitute a part of the earthworm diet (Lemtiri *et al*., 2014). Earthworms play a crucial role in nutrient cycling processes involving C and N (Lemtiri *et al*., 2014). They play two contrasting roles in regulating organic C dynamics, *viz*., a) enhancing organic C mineralization by stimulating microbial activity and b) stabilizing organic C by formation of micro and macro aggregates (Angst *et al*., 2019). They are capable of converting organic matter with relatively wide C:N ratios into forms of lower C:N ratios, which resultantly enhances the nutrient cycling of N (Syers and Springett, 1984).

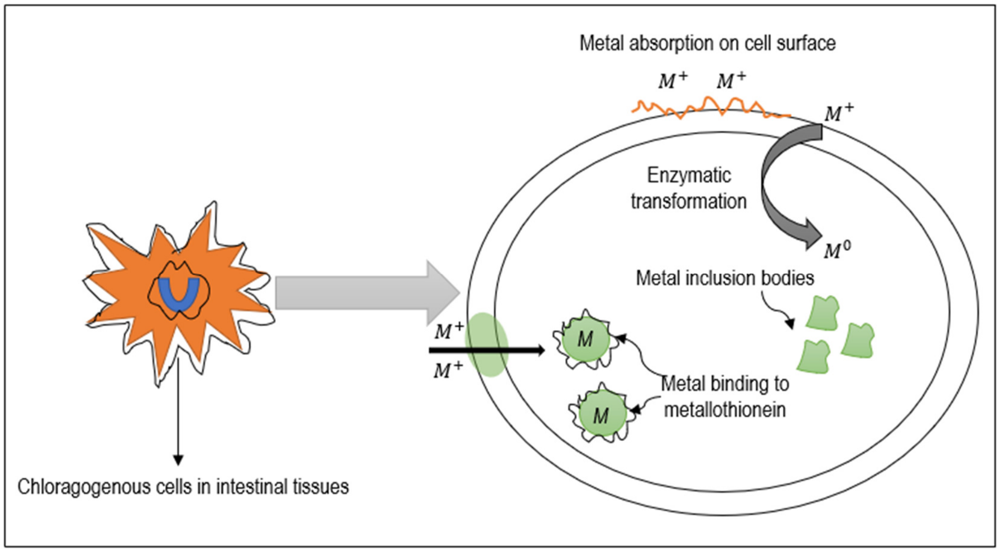

Figure 4. Bioaccumulation and biotransformation of metals in chloragogenous cells (modified from: (Swati and Hait, 2017))

Earthworms are capable of up-taking potentially toxic elements mainly through two pathways – dermal uptake and dietary uptake (Dominguez and Edwards, 2011; Xiao *et al*., 2021). A higher content of mobile metal fractions is resultantly produced as metals are unbounded from their ions and carbonates because of the digestion of degradable organic matter. These mobile fractions get accumulated in the cutaneous tissues as a stress response of the earthworms (Li *et al*., 2009; Swati and Hait, 2017). Organic wastes get mineralized and humified to form simpler or short chain organic acids during biodegradation. These newly formed organic acids form stable metal complexes and/or silicate fractions by binding to the available metal content (Hait and Tare, 2012). The earthworms have adapted to the process of metal accumulation by maintaining a balance between uptake and excretion. The rate of metal excretion increases in earthworms overcoming the metal uptake in tissues which helps them survive the metal induced stress conditions (Li *et al*., 2009; Swati and Hait, 2017). Various metals such as Cd, Pb, Hg, and Zn are stored in the chloragogenous tissues of earthworms (Figure 4) after their accumulation (Song *et al*., 2014; Goswami *et al*., 2016). Different factors like metal type and its exposure level, earthworm species and its physiology and age, production of metal chelating proteins, and substrate characteristics influence the metal accumulation potential and binding mechanism of earthworms (Nannoni *et al*., 2011). The chelation of metals is induced by a low molecular weight protein – metallothionein (MT), wherein this cysteine rich protein chelates metals with the help of their thiol groups and transport them to the chloragogenous tissues (Homa *et al*., 2016). It has been observed that exposure of earthworms to toxic elements like Cd and Hg up-regulates the expression of MT in the intestine (Maity *et al*., 2009; Colacevich *et al*., 2011). However, the metal accumulation potential of earthworms doesn't always correlate with the MT induction in intestines (Goswami *et al*., 2016). Interestingly, the induction of other non-MT proteins which are capable of accumulating such toxic elements has been reported, which explains why this incongruity exists (Hussain *et al*., 2021). Earthworms also accumulate PAHs by dermal absorption and/or intestinal digestion, which are then bio-transformed or biodegraded into more stable harmless compounds (Sinha *et al*., 2008).

Conclusions

The pollution of toxic constituents originating from industrial wastes or sludges has severely affected the environment and human health. Even though considerable progress has been made in bioremediation of such pollutants, the scope of vermicomposting in remediation of such pollutants is yet to be fully explored. As discussed in this review, several factors are inextricably associated with vermicomposting which could accelerate the biodegradation process of such toxic constituents and render it for large-scale implementation. Empirical studies have shown the positive effects of different bulking agents in vermicomposting which could help in chalking out the suitable bulking materials for vermiremediation of different industrial wastes/sludges. The influence of abiotic factors on vermicomposting and the role of different earthworm species also provides valuable insights for making it a more viable process. It can be suggested that vermiremediation can be made a more scalable process with proper knowledge and understanding of the various co-dependent factors. Thus, this study can be taken as an opportunity where further research investigations can be carried out to fill the gaps in developing the vermiremediation process in management of industrial wastes.

Authors' Contributions

SN: Manuscript writing, editing and review; AQ: Manuscript editing and review; SD: Conceptualization, manuscript editing and review. All authors read and approved the final manuscript.

Ethical approval (for researches involving animals or humans)

Not applicable.

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Conflict of Interests

The authors declare that there are no conflicts of interest related to this article.

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