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A review of the vermicomposting process of organic and inorganic waste in soils: Additives effects, bioconversion process, and recommendations

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ABSTRACT

Soil nutrient recovery has emerged as a critical issue to maintain the soil fertility. However, the use of some organic and inorganic chemicals in agricultural and industrial systems gives rise to soil contamination. Advances in biological engineering have empowered for developing vermicomposting technology to decompose desired organic and inorganic wastes in soils. Three clusters of earthworms have been applied including epigeic, anecic, and endogeic to break down organic and inorganic wastes in soils, even though epigeic cluster, for instance *Eisenia fetida*, has been frequently employed for vermicomposting since it can be found readily in soil surfaces and can survive in any environment conditions. This review is designed to cover three potential earthworm clusters for vermicomposting process, earthworm decompose mechanism of organic and inorganic waste, chelation process in earthworm intracellular digestive system to decompose inorganic waste during vermicomposting process, the effect of the presence of materials, microorganism, and treatments during vermicomposting process, and the potential of bio-conversion product. The discovery of complex behaviors of earthworm system for decomposing inorganic waste including heavy metals is also enclosed to contribute a comprehensive overview of the advancements made and forthcoming directions.

1. Introduction

Over the past century, the issue of soil waste has received considerable critical attention globally (Wei et al., 2022). Rapid development of industrial areas, animal husbandry, waste disposal practices, and agrochemicals in agricultural systems have led to increasing numerous contaminants in soils (Zhang et al., 2021b). If treated negligently, the presence of organic and inorganic wastes in the soils can impose extensive threats to the environment and humans because of their possible noxiousness (Marini et al., 2020). For instance, a study reported that 3–5-year-old children in Germany were exposed with lead (Pb) and chromium (Cr) which is 22–28 % higher than 14–17-year-old (Vogel et al., 2021). In Japan, higher concentration of cadmium absorbed in rice has been attributed to the cause of itai-itai disease (Kubota, 2020). In Bangladesh, Kenya, and Zimbabwe, organic and inorganic exposures are linked to adverse diarrheal symptoms, in excess of preterm birth and stunting (Kearns, 2020). Long-term exposure of organic and inorganic wastes has been inspected as the cause of cancer, jaundice, kidney and liver damage (Abdel-Shafy and Mansour, 2016).

Organic and inorganic waste in soils including high concentration of total organic content (TOC), total nitrogen (TN), and antibiotic resistance genes (ARGs) can affect stability and decomposition rate of soils (Ramesh et al., 2019). In addition, as well as heavy metals with high density and high hardness that can affect soil stability and decomposition process, metals with low hardness and toxicity can contribute to soil instability and decomposition (Trentin et al., 2019; Wang et al., 2021a). In agricultural system, soil organic and inorganic waste are able to be influenced by agricultural waste, the use of chemical fertilizer, and pesticides in soils, such as harvest waste, potassium nitrate, ammonium sulphate, fluoroacetate, lead arsenate, phenylmercuric acetate, tetracyclines, and sulfonamide, which does impact on the environment and human health, such as garbage accumulation, cardiac ailment, kidney disorder, respiratory system disease, reproductive disorder, diarrhea, ulcer, and metabolism process (Mie et al., 2017; Rani et al., 2021; Sun et al., 2020). Consequently, recovery techniques are needed to decompose organic and inorganic waste in soils in order to avoid the

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contamination-associated serious health problems.

The exploration among the projected recovery technique has directed to the thought of vermicomposting technology to treat the presence of organic and inorganic contaminants in soils. Vermicomposting technology is eco-friendly technique which breaks down organic waste in soils as well as can degrade inorganic waste in soils (Lukashe et al., 2019; Zziwa et al., 2021). It is affordable and commonly accepted practice to improve the soil fertility by utilizing earthworms as vermicomposting agent that are used in agriculture as soil conditioners (Singh et al., 2020). More than 4000 species of earthworms which are clustered into three ecological groups: epigeic, anecic, and endogeic, only a few belonging epigeic groups have been utilized for vermicomposting process (D'Hervilly et al., 2021). Among epigeic groups, *Eisenia fetida* and *Eudrilus eugeniae* species are widely used for vermicomposting process (Acquah et al., 2021).

In recent studies, various earthworm species had been propounded to decompose organic and inorganic waste as emerging contaminants in soils through vermicomposting process. For instance, *Eisenia fetida* for cow dung and dairy cattle farm decomposition (Huang et al., 2021; Liu et al., 2021), *Eudrilus eugeniae* and *Lumbricus rubellus* for metal remediation (Usmani et al., 2017), *Amynthas robustus* for atrazine degradation (Lin et al., 2018), and *Metaphire guillelmi* for chlortetracycline, ARGs, cadmium, and Tetrabromobisphenol A (TTBA) detoxification in soils (Chen et al., 2017a; Chen et al., 2017b; Yang et al., 2021), *Metaphire posthuma* for phosphate solubilization and plant growth promotion (Biswas et al., 2018), as well as *Allolobophora chlorotica* and *Aporrectodea longa* for restoring bauxite residue mine site (Courtney et al., 2020). Whilst purposeful, these earthworm species decompose organic and inorganic waste by digesting pollutants as a source of nutrients. In addition, earthworm recover soil porosity, texture, structure, drainage, water holding capacity, and aeration, inclusive of diminish erosion and neutralize pH of the soils (Abbott et al., 2018). Furthermore, the role of earthworm for enhancing soil condition can be improved by additives such as microbes and solid substrates. Due to these features, earthworm species demonstrate the potential to be used for vermicomposting process of organic and inorganic wastes in soils and can produce valuable product through bioconversion process.

Quite a few articles are prevailing on the subject of vermicomposting process, reviewing on cattle solid waste management (Yuvaraj et al., 2021), organic waste remediation and composting (Maharjan et al., 2022; Vuković et al., 2021), agricultural waste (Ducasse et al., 2022), organic fraction in municipal solid waste (Ulloa-Murillo et al., 2022), alleviation stress-non stress condition in plants (Makkar et al., 2022), and the application of vermicomposting (Pierre-Louis et al., 2021). To the best of the authors' knowledge, no comprehensive review has ever been described exclusively that focused on the worm composting process to decompose organic and inorganic waste. Furthermore, the discussion concerning three potential earthworm clusters to be used in the vermicomposting process has never been conferred. Based on these observations, this paper attempts to review the physical characteristics of three potential earthworm clusters for vermicomposting process, decomposition mechanism of organic and inorganic waste, chelation process in earthworm intracellular digestive system to decompose inorganic waste during vermicomposting, the effect of the presence of different materials, microorganism, and treatment addition during vermicomposting process, and the potential of bio-conversion product. Owing to the recent advancements in this field, this study becomes an essential review to have better understanding into vermicomposting process in eliminating organic and inorganic wastes in soils and applying vermi-reactor as an advanced vermicomposting technology in future decompose application. In the ecological aspect, discovering and understanding complex behaviors of earthworm digestive system that can chelate inorganic wastes has led to wider use of vermicomposting process, which ingested and released as compounds needed by plants. Traditional literature review method was used to conduct this review, which is initially performed by using a search for specific keywords relevant "vermicomposting process" via Scopus and Google Scholar databases. The narrative synthesis method was used to summarize, synthesis, and draw insight from the collected articles. The information presented in this review represents an overview of vermicomposting process of organic and inorganic waste in soils that focuses only on additives effects, bioconversion process, and recommendations.

2. Earthworm as an essential part of the vermicomposting process

In light of recent events, earthworm is frequently prescribed for vermicomposting issue to eliminate toxic pollutants in soils. Compared to other living organisms, such as bacteria, archaea, algae, and fungi, earthworm have high tolerance for the surroundings, for instance soil acidity level. Earthworms are distributed into three clusters: epigeic earthworm, anecic earthworm, and endogeic earthworm, depending on where they live as seen in Fig. 1. Epigeic earthworm mostly find on the surface of soils in leaf litter. Anecic earthworm is well-known as midden earthworm which typically lives on vertical burrows in soils. Endogeic earthworm lives on horizontal burrows in upper soils layer. Beside three clusters, there is compost earthworm that can eliminate contaminants in soils.

Table 1 lists some species of earthworm obtained in various environmental territories. Earthworm are commonly found in Asian countries, such as Nigeria, Iran, Malaysia, Pakistan, Thailand, India, Laos, Vietnam, Turky, Indonesia, Iran, Myanmar, and China. Apart from Asia, earthworms are also found in several European and American places, such as Brazil, French, eastern Amazonia, and Mexico. These countries have typical environments usually inhabited by earthworms which have moist soil, sandy area, terrestrial area, forest, meadows, croplands, urban areas, water streams, lakes, waterfalls, and riverbanks. It indicates that earthworms in various countries and environmental territories can be easily found and applied for vermicomposting process.

Quite a lot of genera under epigeic earthworm classification are *Eisenia*, *Metaphire*, *Polypheretima*, *Adodrilus*, *Ekitidrilus*, *Pontodrilus*, *Drawida*, several *Amynthas* and several *Holoscolex*. Previous studies have presented that epigeic has pink, violet, reddish and brownish in color pigment, as discussed in Table 1. Their length ranges about 20 mm to ~120 mm. Epigeic species have a tendency to feed on leaf litter, thus, epigeic earthworm species, for instance *Eisenia fetida*, are frequently used for vermicomposting process since they are easily found in the surface of soil and has an ability to survive in an environment full of pesticides, such as insecticides, acaricides, herbicides, and fungicides (Ramnarain et al., 2019; Wang et al., 2012).

Beside epigeic earthworm, anecic earthworm also have color pigmentation. The pigment color of anecic earthworm is pale to pinkish, greyish, reddish and brownish, as seen in Table 1. Some earthworm from genera *Lumbricus*, for instance *Lumbricus terrestris*, has pinkish to reddish-brown in color (McTavish et al., 2020). They have a length up to 600 mm, for instance *Lumbricus badensis* (Kutschera and Elliott, 2010). Compared to epigeic, anecic are longer and have a paler color. They primarily forage on soil surface of organic matter and save themselves in burrows. It is noted that for vermicomposting process, anecic species can process organic and inorganic matter. Previous study demonstrated that *Lumbricus terrestris* are able to break down microplastics in soil (Sanchez-Hernandez et al., 2020). In addition, anecic species have an ability to survive at low temperatures and pH range from 3.5 to 8, indicating the potential utilization of anecic species for the biodegradation of organic and inorganic materials under various acid and alkaline environments.

Different from epigeic and enecic, endogeic species mostly lack color pigmentation or tend to have pale to bluish-greyish color pigment. Several species from genera *Aporrectodea, Philomontanus*, *Drawida, Dendrobaena*, *Healyella*, *Polypheretima, Protozapotecia*, *Metaphire*, and *Diplotrema* are included in endogeic species (Table 1). Endogeic species have a length up to ~190 mm, for instance *Polypheretima insularis*. Compared to epigeic species, endogeic species is longer. Nonetheless,

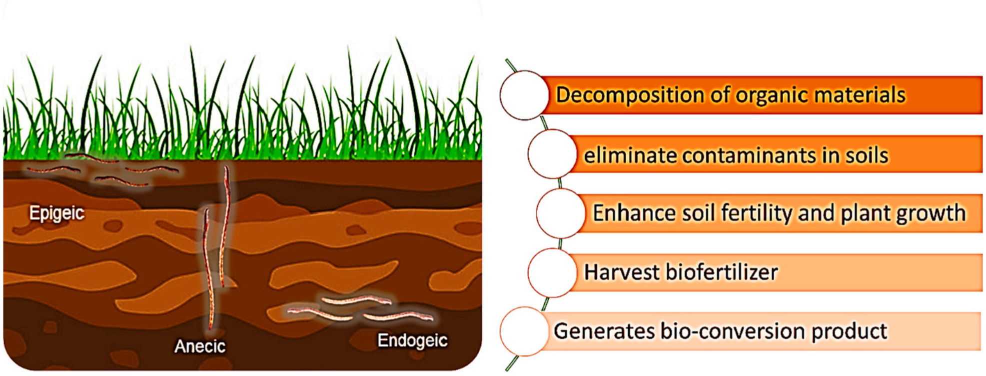

Fig. 1. Epigeic, anecic, and endogeic earthworm as an essential part of the vermicomposting process and its advantages.

endogeic species is shorter than anecic species. Previous study employed endogeic species to remove contaminants from waters, for instance *Metaphire guillelmi* to remove pharmaceutical waste, chlortetracycline and antibiotic resistance genes (Yang et al., 2021), *Aporrectodea caliginosa* to eliminate phenanthrene and cadmium (Elyamine et al., 2018), *Aporrectodea rosea* to reduce microplastics (polylactic acid, HDPE, and microplastic clothing fibers) (Boots et al., 2019), and *Pontoscolex corethrurus* to sense toxicity level of heavy crude oil presence in tropical agroecosystems around oil-processing facilities (del Carmen Cuevas-Díaz et al., 2017).

The presence of earthworm in soils is an important aspect to eliminate organic and inorganic waste through its removal mechanism which accumulated in earthworm bodies, such as skin, gut, organ, and body fluids (Zhu et al., 2021).

The removal mechanism of organic and inorganic waste from the soil using earthworm depends on earthworm's digestive system. Earthworm digestive system has chemical receptors (chemoreceptor) in its mouth and body, pharyngeal glands, and calciferous glands. Chemoreceptors are capable to sense and detect chemical compounds in the soil. Pharyngeal glands and calciferous glands play role in the digestion process. Pharyngeal glands consist of chromaphil cells which generate saliva and proteolytic enzymes, such as proteases, phosphatases, and mucin, for digesting the organic compounds. Proteases convert protein into amino acid, phosphatases solubilize phosphate materials, and mucin softens the material consumed. Calciferous glands secrete a suspension containing calcium carbonate to neutralize the feeding material, regulate calcium ion concentration, and normalize pH in intestine (Zhang et al., 2000). At the last digestion process, enzyme amylase is secreted to break down starch into glucose.

Beside decomposed organic compounds, earthworm intracellular system produces phytochelatin and metallothionein for inorganic detoxification and homeostasis roles (Hussain et al., 2021). Fig. 2 presents that annotation proteins are produced as the adaptability of cell membrane for the presence of inorganic materials (Ratnasari et al., 2021). These proteins transport inorganic materials, such as metals, from extracellular system to intracellular system. In intracellular system, phytochelatin (PC) is produced to chelate soft metal and metalloid ions (mES), such as cadmium (Cd) and arsenic (As) by glutathione (GSH) which contains three essential amino acids, such as glutamine, glycine and cysteine, inducing by the presence of soft metal and metalloids in cell membrane. PC in earthworm digestive system can be utilized to reduce metal and metalloid waste in soils. Previous study introduced phytochelatins (PCs) as non-metallothionein protein or metal induced protein (MIP) and MIP was shown to be rich of glutamic acid which bound Cd by *Eisenia fetida* during vermicomposting process (Hussain et al., 2021). PC can bind mES during chelation process and form PCmES as chelation product. After chelation process, PCmES ingestion by PC can be accumulated in the intestinal area and the chloragogenous tissue. As well as PC production for chelating mES, metallothionein (Me), a cysteine rich metal binding protein, can be excreted to regulate heavy metal stress, neutralizing toxic heavy metals, for instance copper (Cu), nickel (Ni), and zinc (Zn). Me receives heavy metals extracellular digestion product (MES) from extracellular system transferred by annotation protein in cell membrane. After passing annotation protein, MES can enter the intracellular system. MES can bind Me via the chelating process and form MeMES as chelation product.

3. Effect of additives on vermicomposting process

Epigeic earthworm, such as *E. fetida*, is commonly used for vermicomposting process to decompose organic and inorganic soil waste. Zhou et al. (2021a) listed organic residues that were decomposed by *E. fetida*, such as cattle dung, herbal waste, rice straw, soybean straw, garden waste, and tea residues. Another inspection employed *E. fetida* and *Amynthas robustus* to degrade tetracycline which resulted in the decreased tetracycline residues from 3.38 ± 0.37 mg/kg without earthworm to 2.43 ± 0.44 and 2.57 ± 0.30 mg/kg for *E. fetida* and *A. robustus* in sterile soils (Lin et al., 2021). Different results were obtained in natural bulk soils that presented higher removal with 1.87 ± 0.72 and 1.24 ± 0.53 mg/kg for *E. fetida* and *A. robustus* because of the presence of bacterial community in natural bulk soils. Endosulfan lactone was also removed up to 90.86 % in non-sterile solid substrate and 83.86 % in sterile solid substrate using *E. fetida* via vermicomposting (Vázquez-Villegas et al., 2021). In addition, the presence of other materials, organism, and treatments in soils allows predisposing degradation efficiency of toxic pollutants and vermicomposting process (see Table 2).

To understand the presence of other materials or treatments in soils which affect vermicomposting process, several studies have explored the effect of the additives physically, biologically, and chemically on vermicomposting process. Physically, the temperature of 10–40 °C was favorable for vermicomposting process using *E. fetida*. The addition of gut bacterial population at 30 °C could enhance vermicomposting process. Nonetheless, the temperature of 50 °C could inhibit vermicomposting process and enzyme activities, even though *E. fetida* can tolerant the temperature from 10 °C to 50 °C (Zhou et al., 2021b).

Recent study evaluated the effect of biomass ash (BA) presence on pH for solubilizing nutrients during vermicomposting process to manage dairy cattle manure as agro-industrial waste (Turp et al., 2021). Higher concentration of BA can increase pH value with 6.81, 7.69, 7.74, and 7.76 for 0 % (T_o), 3.5 % (T_1), 7.0 % (T_2), and 10.0 % (T_2) of BA addition (v/v). Furthermore, BA addition (v/v) could reduce phosphorus, organic matter (OM %), and nitrogen (N %) solubilization from 79 % to 69 %, from 64 % to 57 %, and from 2.20 % to 1.82 % for T_1-T_3. It indicated that BA presence with pH incline did not assist to increase the solubilization of nutrients during vermicomposting process. Other bio-waste products addition, bio-drying waste and bio-char, confirmed that they were able to reduce 25.4–38.7 % of total organic contents (TOC) after

Table 1
Earthworm species, genera, and characteristics in different regions.

Earthworm species	Genera	Clusters of earthworms[a]	Color/body length (mm)	Country	References
Lumbricus rubellus	Lumbricus	E	Reddish to semi-transparent/ 95–105	Europe	(Anderson et al., 2017)
Aporrectodea caliginosa	Aporrectodea	N	Grey/60	Great Britain	(Pérez-Losada et al., 2009)
Lumbricus terrestris	Lumbricus	A	Pinkish to reddish-brown/		(McTavish et al., 2020)
Lumbricus badensis	Lumbricus	A	Brownish to black/600	Germany	(Kutschera and Elliott, 2010)
Adodrilus stephana	Adodrilus	E	Brownish/36	Nigeria	(Csuzdi et al., 2020)
Ekitidrilus alabataensis	Ekitidrilus	E	Brownish/36		
Paranematogenia eyinwaensis	Paranematogenia	N	No pigment/105		
Imekodrilus hexagastricus	Imekodrilus	N	No pigment/82		
Philomontanus sarii	Philomontanus	A	Red violet/101–114	Iran	(Bozorgi et al., 2019)
Philomontanus mahmoudi	Philomontanus	N	Pale/51–70		
Philomontanus baloutchi	Philomontanus	A	Red violet/123–140		
Pontodrilus perrier	Pontodrilus	E	Red/28–136	Malaysia and Thailand	(Seesamut et al., 2018)
Drawida polydiverticulata	Drawida	N	Bluish/50–73	India	(Narayanan et al., 2017)
Drawida thomasi	Drawida	N	Bluish/55–66		
Glyphidrilus nanensis	Glyphidrilus	A	Pale brown and red to pink/ 72–99	Thailand and Laos	(Chanabun et al., 2017)
Glyphidrilus satunensis	Glyphidrilus	A	Pale brown and red to pink/ 131		
Glyphidrilus chiangraiensis	Glyphidrilus	A	Pale brown and red to pink/ 158		
Glyphidrilus namphao	Glyphidrilus	A	Pale brown and red to pink/92		
Glyphidrilus sekongensis	Glyphidrilus	A	Pale brown and red to pink/ 134		
Glyphidrilus namdonensis	Glyphidrilus	A	Pale brown and red to pink/92		
Glyphidrilus champasakensis	Glyphidrilus	A	Pale brown and red to pink/ 301		
Dendrobaena pavliceki	Dendrobaena	E	Pale slight reddish/36–48	Turkey	(Szederjesi et al., 2018)
Dendrobaena taurica			No pigment/45–46		
Healyella zicsii					

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Table 1 (*continued*)

Earthworm species	Genera	Clusters of earthworms[a]	Color/body length (mm)	Country	References
	Dendrobaena	N			
			No pigment/84–109		
	Healyella	N			
Polypheretima dorsotheca	Polypheretima	N	Grey/60–138	Kien Giang Province, Vietnam	(Nguyen et al., 2017)
Polypheretima insularis					
		N	Light grey/95–191		
Drawida alishanensis	Drawida	N	Pale grey/35–50	Taiwan	(Shen et al., 2018)
Drawida fenqihuensis					
			Pale grey/47		
		N			
A. longiprostaticus	Amynthas	N	Light grey/51–71	Vietnam	(Nguyen et al., 2020b)
A. dorsomorrioides			Transparent/59–95		
		N			
A. minhdam			Pale color/59–95		
A. ocularius		N	Pale color/65–68		
		N			
Amynthas catenatus	Amynthas	N	Whitish grey/51–54	Vietnam	(Nguyen et al., 2020a)
A. phuquocensis			Greyish brown/74–145		
	Amynthas	N			
			Greyish brown/139–170		
A.poropapillatus					
	Amynthas	N			
P. vungtauensis	Pheretima	A	Greyish brown/132–169	Vietnam	(Nguyen et al., 2018)
	Kinberg				
Amynthas whitteni	Amynthas	E	Black-pale pink/190–265	Myanmar	(Bantaowong et al., 2020)
Amynthas demptus	Amynthas	E	Brown purple/90–130	China	(Yuan et al., 2019b)
Amynthas lacustris			Light grey/66–71		
Metaphire reclusa	Amynthas	N			
			Tawny pigment/110–149		
	Methapire	N			
Diplotrema chajulensis	Diplotrema	N	No pigment/20–27.7	Mexico	(Fragoso and Rojas, 2018)
			No pigment/17.6–30		
Lavellodrilus sheylae					
	Lavellodrilus	N			
Glossoscolex maschio	Glossoscolex	A	brown/250.2	Brazil	(M and Brown, 2018)
Glossoscolex embrapaensis			No pigment/84.7		
	Glossoscolex	N			
Fimoscolex nivae			Yellowish/66.71		
	Fimoscolex	N			
Polypheretima cokelat	Polypheretima	A	Pinkish brown/54–185	Sulawesi, Indonesia	(Fahri et al., 2017)
Polypheretima sahlani			Purplish brown/152–195		
Polypheretima elongatoides	Polypheretima	A	Yellow brownish/118–240		
Polypheretima kalimpaaensis			Purplish pink/124–156		
	Polypheretima	A			
	Polypheretima	A			
Polypheretima suwastikai	Polypheretima	A	Brownish red/135–165	Sulawesi, Indonesia	(Fahri et al., 2018)
Polypheretima tadulako					
			Darkish blue/217–340		

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Table 1 (*continued*)

Earthworm species	Genera	Clusters of earthworms[a]	Color/body length (mm)	Country	References
	Polypheretima	A			
Metaphire iranomala	Metaphire	A	Dark grey/157–228	Vietnam	(Nguyen et al., 2021)
Metaphire decemtheca			Dark grey/64–185		
	Metaphire	A			
Polypheretima medialis	Polypheretima	N	Whitish grey/92–97	Vietnam	(Lam et al., 2018)
Polypheretima tabhingensis					
			Dark brown/80–85		
	Polypheretima	E			
Glyphidrilus tonywhitteni	Glyphidrilus	E	Pale brown/52–120	Myanmar	(Chanabun et al., 2020)
Pontoscolex awa	Pontoscolex	E	A pigmented/66	Brazil	(Sousa et al., 2020)
Amynthas dissimilis	Amynthas	A	Light purple pigment/125–142	Guangxi Province, China	(Jiang et al., 2018)
Amynthas anteporus			No pigment/30–47		
Amynthas marsupiformis	Amynthas	N			
			Pink/58–70		
	Amynthas	E			
Amynthas crassitubus	Amynthas	A	Yellowish brown/78–130	Guangxi Province, China	(Dong et al., 2018)
Amynthas stabilis			Tan pigment/61–68		
	Amynthas	E			
Amynthas hiatus	Amynthas	A	Puce/156	Yunnan, China	(Yuan et al., 2019a)
Amynthas recavus	Amynthas	E	Pink and light brown/58–64		
			No pigment/110–143		
Metaphire daliensis					
	Metaphire	N			
Drawida ganini	Drawida	E	Black/66–121	Heilongjiang Province, Northeast China	(Zhang et al., 2021a)
Amynthas dispersus	Amynthas	A	Brown/75–110	Guangdong Province, China	(Sun et al., 2018)
Amynthas shanghangensis			Brown/210–241		
	Amynthas	A			
Amynthas dentiformis					
			Brown/129–151		
Metaphire sanmingensis					
	Amynthas	A			
			Brown/55–113		
	Amynthas	E			
Metaphire sedimensis	Metaphire	A	NA/140–177	Kedah, Malaysia	(Ng et al., 2018)
Metaphire hijaunensis					
	Metaphire	E	NA/66–87		
Cataladrilus porquerollensis	Cataladrilus	N	No pigment/45–51	French Mediterranean	(Marchan et al., 2020)
Scherotheca portcrosana			faint brown-grey/80		
	Scherotheca	N			
Righiodrilus gurupi	Righiodrilus	N	No pigment/65	eastern Amazonia	(Santos et al., 2017)
Righiodrilus viseuensis					
Righiodrilus moju					
			No pigment/95		
	Righiodrilus	N			
			No pigment/86		
	Righiodrilus	N			
Holoscolex dossantosi	Holoscolex	N	Milk-white/40	Maranhão, Brazil	(HernÁndez-garcÍa et al., 2018)
Holoscolex alatus					
Holoscolex fernandoi					

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Table 1 (*continued*)

Earthworm species	Genera	Clusters of earthworms[a]	Color/body length (mm)	Country	References
			Beige/64		
	Holoscolex	E			
			No pigment/61		
	Holoscolex	E			
Amynthas haikouensis	Amynthas	N	No pigment/29–80	Hainan Island, China	(Zhao et al., 2017)
Amynthas lucidus					
			Khaki/116–174		
Amynthas flexuosus	Amynthas	A			
Metaphire fortuita			Light brown/112		
	Amynthas	A			
			Khaki-dark grey/295		
	Metaphire	A			
Protozapotecia acaxetlensis	Protozapotecia	N	No pigment/55–78	Mexico	(Cervantes and Fragoso, 2018)
Protozapotecia oyametlensis			No pigment/66–85		
	Protozapotecia	N			
Metaphire bahli	Metaphire	E	Reddish brown/76–121	India	(Narayanan et al., n.d.

[a] Clusters of earthworm: E = epigeic, A = anecic, and N = endogeic; NA = not available.

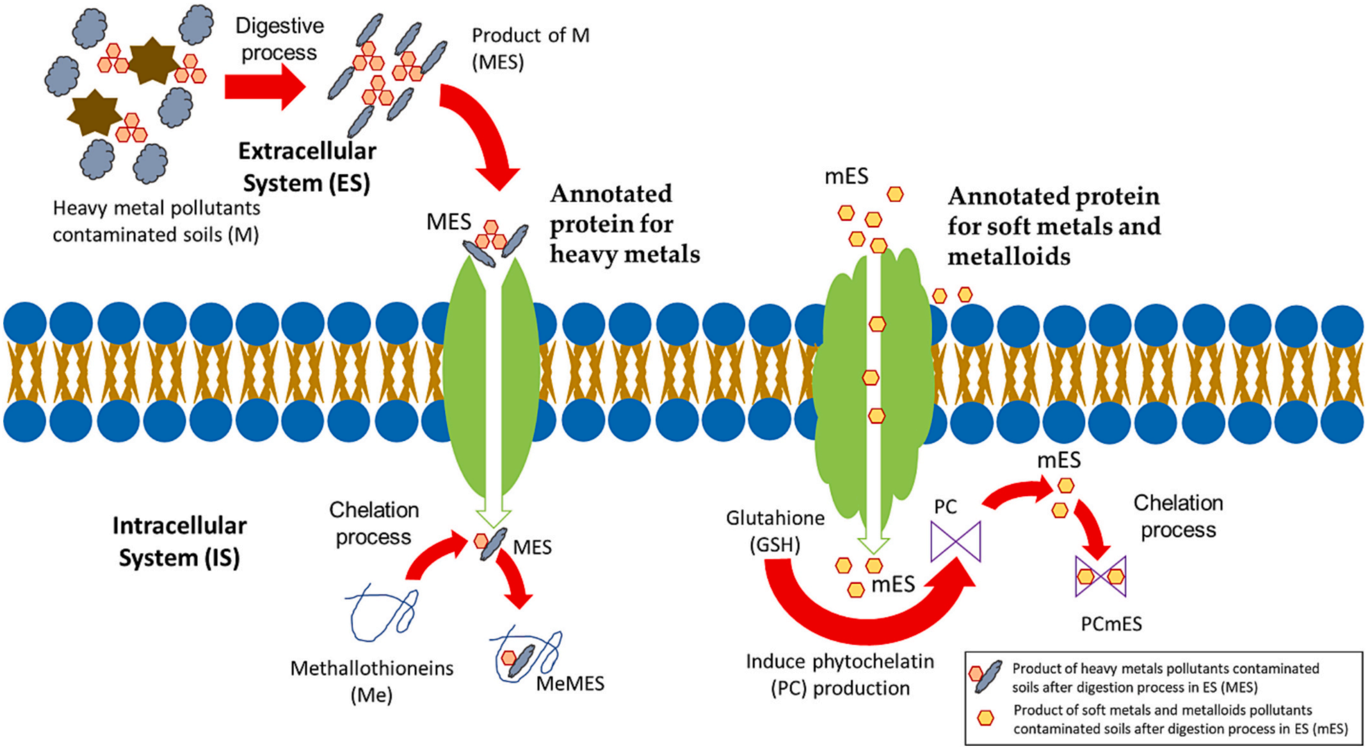

Fig. 2. Schematic diagram indicating the decomposition of inorganic materials in the extracellular and intracellular system during the vermicomposting process mechanism: ROS, annotated protein, enzyme secretion, and chelation.

vermicomposting process, adding *Gleditsia sinensis* pod powder (GSPP), rice husk bio-char (RHB), coconut shell bio-char (CSB), GSPP-RHB, and GSPP-CSB with 29.2, 25.4, 29.7, 31.2, and 39.7 % of TOC reduction (w/w) (Gong et al., 2021). Without supplementation of bio-char, the elimination of heavy metals, chromium (Cr), was achieved ~30–40 % (ppm/ppm) higher compared to bio-char addition during vermicomposting process (Tasnim et al., 2021). Nonetheless, the addition of bio-char increased seed germination and root elongation which is related to nitrogen presence in soils. It indicated that the addition of bio-waste material in the vermicomposting process affects plant growth,

Table 2
Effect of additives in vermicomposting process.

Earthworm species	Additives	Finding	References
Eisenia fetida and *Amynthas robustus*	Bacterial community	higher removal with 1.87 ± 0.72 and 1.24 ± 0.53 mg/kg with the presence of bacterial community	(Lin et al., 2021)
Eisenia fetida	Non-sterile solid substrate	Endosulfan lactone was also removed up to 90.86 % in non-sterile solid substrate and 83.86 % in sterile solid substrate	(Vázquez-Villegas et al., 2021)
Eisenia fetida	Temperature and gut bacteria population	The addition of gut bacteria population at 30 °C could enhance vermicomposting process.	(Zhou et al., 2021b)
earthworm	Biomass ash (BA), ph	BA presence with pH incline did not assist to increase the solubilizing nutrients during vermicomposting process	(Turp et al., 2021)
Eisenia fetida	Bio-drying waste and bio-char	25.4–38.7 % of TOC reduced	(Gong et al., 2021)
Eisenia fetida	Bio-char	Without supplementation of bio-char, the elimination of heavy metals, chromium (Cr), was achieved $\sim$30–40 % higher compared to bio-char addition during vermicomposting process	(Tasnim et al., 2021)
Eisenia fetida	*T. asperellum* and *T. virens*	fast-tracked the stabilization of vermicomposting process	(Busato et al., 2021)
Eisenia fetida and *Eudrilus eugeniae*	*Parthenium hysterophorus*	Vermicomposting process increased up to 30–40 %	(Devi and Khwairakpam, 2021)
Eisenia fetida	Microplastics (MPs)	$>$200 μm of MPs particles were decreased, whilst $<$100 μm of MPs particles were increased up to 27.9 %	(Zhong et al., 2021)
Eisenia fetida	LDPE MPs	$<$100 μm of LDPE MPs was ingested nearly 30 % in soils	(Chen et al., 2020)

solubilization, and reduction of pollutants in the soil.

Beside bio-waste material addition, biologically, vermicomposting process also can be influenced by the presence of microorganisms, such as fungi, bacteria, and microbial community. Previous studies employed *Trichoderma* sp., *T. asperellum* and *T. virens*, to TOC from monensin contaminated chicken manure in soils (Busato et al., 2021). *Trichoderma* sp. enhanced the formation of enzyme degrading up to noteworthy levels, for instance cellulose and xylanase. Thus, *Trichoderma* sp. fast-tracked the stabilization of vermicomposting process. Vermicomposting process was improved by 30 %–40 % by *Parthenium hysterophorus* addition (Devi and Khwairakpam, 2021). Also, adding mature vermicompost content can increase the molecular complexity and aromaticity indicating the maturity and stability which improves the efficiency of vermicomposting (Hu et al., 2021b).

Besides decomposing organic and inorganic material, the addition of MPs in vermicomposting process was reported to have a negative impact in the vermicomposting process after 20 days of exposure. In vermicomposting process, MPs was ingested smaller particles in earthworm digestive systems. In the vermicomposting-reactor, $>$200 μm of MPs particles were decreased, whilst $<$100 μm of MPs particles were increased up to 27.9 % (Zhong et al., 2021). Similar finding was also obtained that $<$100 μm of LDPE MPs was ingested nearly 30 % in soils (Chen et al., 2020). The size transformation of MPs decomposed during vermicomposting process is related to the digestion mechanism in the earthworms (Zhong et al., 2021). The significant increase in reactive oxygen species (ROS) levels takes place as a metabolic reaction to the contact of MPs in the digestive system. Glutathione enzyme have an important role for detoxifying MPs in cellular membrane of digestive system, eliminating extremity of ROS, and covering cells from the destructive effect of ROS.

4. Potential bioconversion of vermicomposting process

The use of earthworm for vermicomposting process has several advantages too as seen in Fig. 1. Besides reducing organic and inorganic waste, vermicomposting can improve soil structure, enhance plant growth, neutralize soil pH, harvest biofertilizer, and generate bioconversion product. Previous studies analyzed carbon dioxide and methane production during vermicomposting process of sewage sludge which released up to 11.6 % of carbon dioxide (CO_2) and 0.6 % of methane biogas (Dume et al., 2021). CO_2 evolution in vermicomposting process is the direct technique of compost stability since it is derived from biological activity of carbon content regarding to aerobic respiration (Khwairakpam and Bhargava, 2009). Another investigation found the 44.2–68.3 % of methane content in biogas by combining bioconversion of vermicomposting and anaerobic digestion to manage agro-industrial poultry waste (Niedzialkoski et al., 2021). It is well known that methane is produced during bioconversion process which could possibly be an alternative energy source. Thus, methane is one of crucial emission which need an attention regarding to its potential.

Devi and Khwairakpam (2020) described the increase in major nutrient as a result of vermicomposting process of *Lantana camara* up to 2.78 % of total kjeldahl nitrogen (TKN) and 10.65 % of total phosphorus (TP) by employing *E. fetida* and *Eudrilus eugeniae* from $\leq$2.03 % of TKN and $\leq$2.03 % of TP. It specified that vermicomposting process has the potential to enrich soil fertility by increasing the percentage of major nutrients. Further study inspected that C/N ratio, nitrate content, ammonium concentration, phosphorus content, and potassium had been increased from 21, 78 mg/kg, 14 mg/kg, 92 mg/kg, and 142 mg/kg to 32, 134 mg/kg, 139 mg/kg, 521 mg/kg, 1912 mg/kg, respectively (Przemieniecki et al., 2021). On the contrary, another investigation presented that C/N ratio in vermicomposting process was influenced by the activity of microbial enzymes of arylamidase and β-glucosidase, in primary and secondary sludges (Ganguly and Chakraborty, 2018). C/N ratio from primary sludge was reduced up to 70 % after 30 days of vermicomposting process, at the same time as C/N ratio from secondary sludge diminished up to 82 %. Leucine-arylamidase activity prepared from primary sludges ($\sim$250) was relatively higher than secondary sludge ($\sim$200) in 30th day, whilst β-glucosidase activity prepared from secondary sludge was relatively lower ($<$20,000) than primary sludge ($\sim$20,000). However, it indicated that the presence of microbial enzymes can affect the values of the C/N ratio after vermicomposting process regarding the soil fertility.

As well as soil fertility, organic solid wastes are able to convert to bio-fertilizer via vermicomposting process. Ning et al. (2021) employed a coupled thermophilic composting and vermicomposting process which was co-assisted by *Trichoderma* to produce high value-added bio-fertilizers. Empty fruit bunches were bio-converted into organic fertilizer using *Eudrilus eugeniae* (Lim et al., 2015). Calcium, phosphorus, potassium, and magnesium increased with the percentage of 39.38–373.17 %, 15.15–390.54 %, 45.55–153.66 % and 55.86–370.93 % (w/w), whilst C/N ratio had a decreasing value from 76.24 % to 11.24 % (w/w) after 12 weeks of vermicomposting process. *Eisenia andrei* converted *Cytisus scoparius* (L.) Link into a nutrient rich and stable material with no phytotoxicity after 42 days of vermicomposting process (Domínguez et al., 2018). In another finding, via vermicomposting process, *E. fetida* converted citronella bagasse into bio-fertilizer product (Boruah et al., 2019). The study discovered that the blending composition of each substrate improves the quality and quantity of vermicomposting product, for instance a mixture of citronella bagasse and paper mill sludge in 3:2 ratio. Furthermore, vermicomposting maturity is projected by C/N ratio, humification index, and ash profiles. An alternative integrating treatment was proposed by designing vermi-reactor with two bed compartments to eliminate antibiotic resistance genes (ARGs) during vermicomposting of excess activated sludge (EAS) and fewer vegetable waste (FVW) (Li et al., 2021). Pursuant to qualitative analysis, there was a significant reduction of relative abundance of ARGs in substrate compartment for vermicomposting process of EAS and FVW. It is indicated that integrating treatment is a promising technique to be developed in order to obtain better effectiveness for the vermicomposting process.

5. Prospects and recommendations

It has been demonstrated that earthworms are mostly employed for vermicomposting process (Zhou et al., 2021a). *E. fetida* is one of earthworm's species which is frequently employed for vermicomposting process. It promotes natural composting for more than a few wastes, for instance pig manure (Zhou et al., 2021b), dairy cattle manure (Turp et al., 2021), perishable garbage (Hu et al., 2021a), chicken manure (Busato et al., 2021), sewage sludge (Hu et al., 2021b), municipal waste (Srivastava et al., 2021), spent drilling fluid (Wang et al., 2021b), cow dung (Mago et al., 2021), food and beverage industries (Katakula et al., 2021). Other species are also mentioned for vermicomposting process, such as *Eudrilus eugeniae* (Acquah et al., 2021), *Amynthas robustus*, (Lin et al., 2021) and *Aporrectodea caliginosa* (Sheikh et al., 2021). These species were evaluated to compost quite a lot of organic and inorganic wastes, such as human excreta, tetracycline, dill weed and cow manure. Thus far, there is no report to demonstrate the usefulness of other species from quite a few genera, such as *Glyphidrilus*, *Holoscolex*, *Drawida*, *Righiodrilus*, *Metaphire*, and *Glossoscolex*, in vermicomposting and degradation process. Hence, several possibilities can be included in future studies.

For material addition, previous studies explained that the elimination of Cr was achieved ~30–40 % higher without supplementation of bio-char compared to bio-char addition during vermicomposting process (Tasnim et al., 2021). Even though with bio-char addition the effective removal of Cr is lower, the addition of bio-char increased seed germination and root elongation, which was related to the presence of nitrogen in the soil. For microorganisms' addition, vermicomposting process was improved by 30–40 % (w/w) by *Parthenium hysterophorus* addition (Devi and Khwairakpam, 2021). Microbes improve the formation of enzyme degrading to noteworthy levels, maturity, and stability. Thus, it is suggested to duly understand the effectiveness of bio-char presence and to employ microbes on vermicomposting process.

Generally, organic and inorganic wastes are easy to be composted and degraded in soils using vermicomposting technique. Different types of MPs have different properties, for instance biodegradable and non-biodegradable MPs. MPs degradation using vermicomposting technique requires an attention. Some non-biodegradable MPs cannot be properly degraded by earthworms through vermicomposting technique. Furthermore, the composted MPs are found in the earthworm's body and present a hazard. Earthworms only reduce the size of the degraded MPs which are partly contained in their bodies and partly ingested into the soil (Zhong et al., 2021). The effect of MPs in earthworms' bodies needs to be further identified in future studies.

It is well-known that earthworm intracellular system is related to annotation protein, phytochelatins, and metallothionein for inorganic detoxification and homeostasis roles (Hussain et al., 2021). Phytochelatin production is induced by glutathione enzyme for chelating soft metal and metalloid compound. Glutathione enzyme plays a role as a metabolic process and adaptation in intracellular digestive system regarding to its biotransformation. The biotransformation of glutathione enzyme in earthworms' bodies is still currently unknown. Chemical metabolic pathway and conjugation of glutathione enzyme for inorganic and organic waste requires to be explored in the future. Therefore, further studies are properly projected to focus on biotransformation mechanism, metabolic pathway and conjugation of glutathione enzyme during vermicomposting process.

Vermicomposting also generates bioconversion products, for instance methane as biogas which could be an alternative energy source and bio-fertilizer to maintain soil fertility (Boruah et al., 2019; Dume et al., 2021). These bioconversion products need to be harvested using proper techniques. One of the proper techniques for harvesting biogas and bio-fertilizer as value added product is by integrating vermicomposting system with biogas digester. Another alternative technique is to design vermi-reactor which has two compartments, a substrate compartment and a bed compartment, as seen in Fig. 3 (Li et al., 2021). Integrating vermicomposting and biogas digester systems or vermi-reactor with two compartments can compost organic and inorganic waste whilst generating biogas and bio-fertilizer. Further research is needed to better accomplish the challenges.

6. Conclusion

The insights gained from this review may be of assistance to decompose and eliminate organic and inorganic waste in soils through vermicomposting process using earthworms. As a result of their ability to survive in various environments conditions, *E. fetida*, an epigeic earthworm are commonly used for vermicomposting. The primary decomposes mechanism of organic and inorganic wastes involve enzyme secretion including excretion of Me and PC. The effects of additives, physically, chemically, and biologically, during vermicomposting process have been reviewed. Physically, the temperature of 10–40 °C was favorable for vermicomposting process using *E. fetida*. The addition of some microorganisms such as fungi and bacteria can improve vermicomposting process. In general, earthworms demonstrate a great ability during vermicomposting process and can be an alternative to degrade organic and inorganic waste in soils. In addition, vermicomposting process has potential to convert organic wastes into value-added products.

CRediT authorship contribution statement

Anisa Ratnasari: Writing – original draft, Conceptualization, Writing – review & editing. **Achmad Syafiuddin:** Writing – original draft, Conceptualization, Writing – review & editing. **Muhammad Aamer Mehmood:** Writing – review & editing. **Raj Boopathy:** Conceptualization, Writing – review & editing.

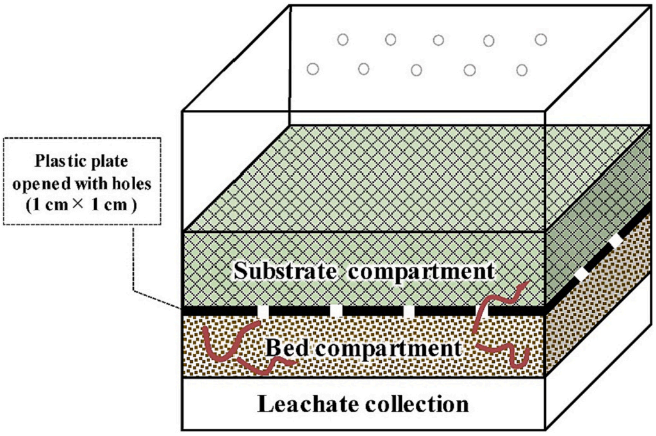

Fig. 3. Vermi-reactor design: a substrate compartment and bed compartment (Li et al., 2021).

Declaration of competing interest

The authors do not have any conflicts of interest with other entities or researchers regarding a publication of their data. Any opinions, findings, conclusions and recommendations expressed in this publication are those of the authors and do not necessarily reflect the view of the funding agency.

Data availability

No data was used for the research described in the article.

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