Chapter 2

Review of literature

2.1 Introduction

Urbanization growth results in the generation of a considerable amount of solid waste around the globe that causes inevitable and alarmingly serious environmental risks [1]. Among several valorization techniques composting and vermicomposting processes are recognized as economically and ecologically compatible technologies [2]. However, vermicomposting is more efficient than composting because the decomposition rate of organic matter is combined action of earthworms and their gut-associated microorganisms than composting [3]. Vermicomposting is a well-known and simple biotechnological process of converting wide ranges of organic waste materials, including their resistant components, into nutrient-rich organic fertilizers by deploying specific groups of earthworm species [4]. Several studies reported significantly greater nutrient and plant growth-promoting enzyme levels in vermicompost compared to compost prepared without the help of earthworms [5,2,6,7]. The efficiency of the technology is primarily regulated by the activity of earthworms and their intestinal microflora. Therefore, the success of vermitechnology largely depends on the condition of the reactors and substrate composition where the earthworms are introduced [8,9]. In nature, earthworms return the carbon locked inside dead organic debris into the soil. They drag fallen plants and other biowaste materials down from the surface soil and eat them, enriching the soil [10]. Eventually, the potentially toxic substances in such materials are detoxified by earthworms through diverse pathways.

Vermitechnology is a valuable method for converting solid waste into useful products. The combined effort of earthworms and their gut-associated microorganism troop drives the decomposing process of the organic matter at a swift with a tremendous significant advantage over composting [2,3]. The vermicomposting end product depends on earthworm biomass concerning different earthworm species, feedstocks, and prevailing conditions [12]. Ansari et al. (2015)[13] reported that organic waste effectively recycling is a novel work toward solid waste management. An earthworm can mineralize organic waste by communicating the action of the gut microorganism.

As such, earthworms' profound metabolic and reproductive abilities have enabled them to adapt to environmental fluctuations. Their high consumption and assimilation potentials are utilized in vermicomposting techniques. Therefore, it is essential to provide appropriate conditions, including feedstock composition, moisture, temperature, aeration, pH, and several other attributes, to transform waste materials into enriched products successfully. This review describes the significance of relevant aspects of vermitechnology and quality control measures of the end product from a critical viewpoint.

Vermicomposting Process – A comparison with composting

The process of composting technology has evolved from the concept of aerobic composting. However, it is a substantially different technique from composting concerning biochemical and biophysical changes. Beddard(1883) [14]reported the use of earthworms for degrading waste materials was probably mentioned. Since the prospects for earthworms for sensitization of arrays of solid wastes have been extensively studied (Edwards and Arancon,2004; Arancon et al., 2008),[14,[15] on the other hand, the composting process relies on indigenous microorganisms for decomposing organic matter [16] . A comparative assessment of both techniques would be beneficial for understanding the core differences between the two.

Table 2.1 presents the significant features of the two systems in short.

Table 2.1: Difference between Composting and Vermicomposting

Sl. No.	Features	Composting	Vermicomposting	Reference
1	Process	Aerobic or anaerobic	Aerobic	[17]
2	Agents	Microorganism	Earthworm &microorganism	[4];
3	Process mechanism	Microbial enzyme mediated	Earthworms and their intestinal microflora induced enzymatic decomposition	[18]
4	Thermal condition	Mesophilic/ thermophilic	Mesophilic	[19]
5	End product quality	Friable with mineralized nutrient, microbial biomass, enzymes	Friable with higher contents of mineralized nutrients and greater proliferation of microbes and their enzymes	[20]

The composting process involves thermophilic and mesophilic conditions when the system temperature ranges between 45-700C [21]. The thermophilic stage occurs within a week from the initiation of the composting process, indicating the rapidity of organic matter decomposition via the acceleration of microbial respiration. The mesophilic phase commences as soon as the microbial activity stabilizes and continues until the mineralization process ends [20,19]. In contrast, vermicomposting is entirely a bio-oxidative process involving only the mesophilic condition [3]. However, a favorable condition is created for the latent microbial population in the feedstocks in composting reactors, transforming the feedstocks into stabilized and nutrient-rich compost characterized by a typical friable texture. However, the process of vermicomposting runs in a phasic manner, schematically presented in **fig 2.1.**

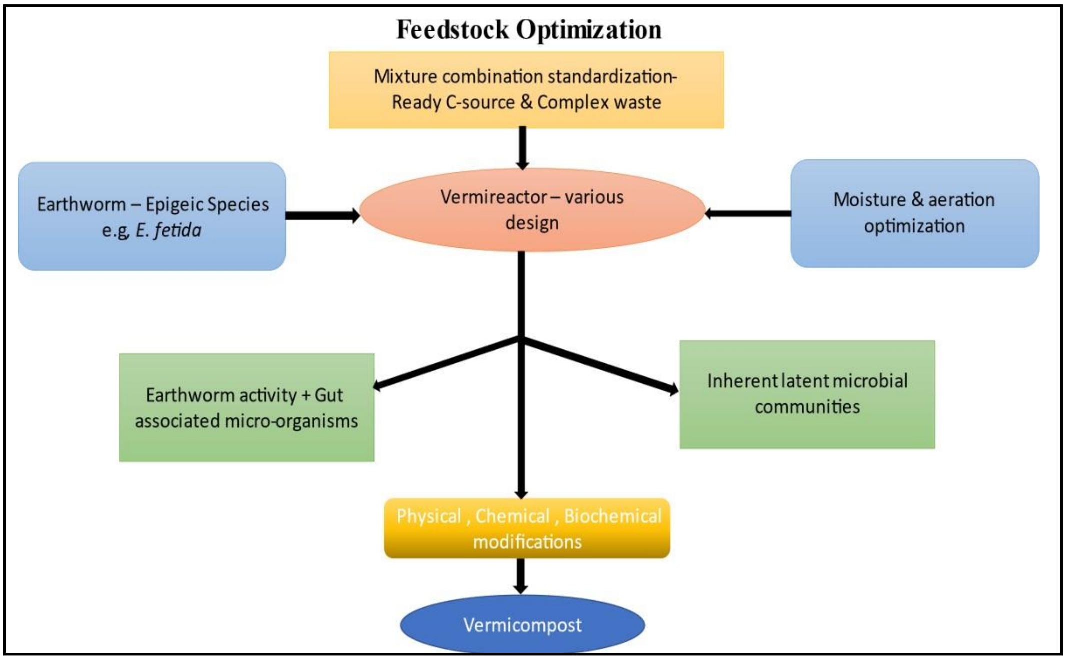

Figure 2. 1: Graphical representation of the experiment

The earthworms voraciously ingest the feed materials and grind them into finer particles in the vermireactors. Eventually, the gut microbiota of the earthworm degrades the ingested feed materials through the accelerated release of a wide range of enzymes, and the worms excrete a significant portion of the digested feedstocks along with the active microflora[3]. The burrowing, feeding, and excretory activity of the earthworm powerfully activates the indigenous microflora of the feedstock, thereby accelerating the decomposition process insignificant manner **(Fig 2.1)**. As a result, the diversity of microbial communities, enzymes, and fatty acids was more spectacular in vermicompost thanin compost [9].

Overall, vermitechnology promotes more excellent nutrient and plant growth enzymes than aerobic composting [16,21,22,7]. The earthworms and their gut microbes regulate the efficacy of vermitechnology [25]. Earthworms play the leading role in returning the carbon locked in the dead organic materials in the soil by consuming them and thus augmenting the soil nutrient [10]. Thus the conversion of the waste materials into nutrient-rich manure by the action of earthworms is known as vermicomposting.

Process optimization of vermitechnology:

The efficiency of vermicomposting systems largely depends on several factors. Das et al.,2020 critically reviewed the available information on major regulatory factors for vermicomposting and coined those physical attributes like texture, color, density, water holding capacity, and temperature are vital indicators of vermicompost and compost quality. Several studies have promulgated that chemical parameters like C/N ratio, macro (N, P, K, Ca, Mg, and S) and micro (Fe, Mn, Cu, Zn, B, Mo, etc.), nutrient availability, and cation exchange capacity are strong quality indicates for any composting system [24,12,25]. Few studies also emphasized that microbial attributes (Microbial counts, microbial biomass carbon and nitrogen, microbial respiration, microbial quotient, etc.) are the most vital quality parameters for composting and vermicomposting because microbial activities and proliferation predominantly regulate both processes. [26,27,9,28]. However, the vermicomposting process is also greatly influenced by earthworm fecundity (Population, growth of worms, cocoon production, body weight, and length) [31]. The desired quality of the end products (Compost and vermicompost) can only be attained through the optimization of standardization of the process conditions. **Tables 2.2 and 2.3** provide comprehensive accounts of the factors determining end product quality and related scientific insights. The tables depict that various complex waste materials could be successfully transformed into valuable manures using vermitechnology. The quality of the end products could be assessed based on the changes in several attributes.

Table 2.2: An account of vital physico-chemical attributes for assessing the composting and vermicomposting status

Sl. No.	Physical & microbial attributes	Favourable status	Reference	Chemical attributes	Favourable status	Reference
1	**Temperature**	27-300 c,29-350c, 25-370c	[7],[61],[1],[62]	**pH**	6.42,7.33,4.2-8.0, 7.30,5.5-8.5	[7],[61],[1],[43],[62]
2	**Moisture**	40-50 %, 65-70%, 50-90%	[55][63][43][62]	**TOC%**	2.78, 18.0	[61][43]
3	**Bulk density**	1.12	[61].	**Total N**	0.73, 1.78	[61],[43].
6	**Reactor Size &Shape**	20 kg of substrates Truncated cone shape with perforated wall	[58],[31].	**C/N**	8.36, 25	[61],[1]
7				**Total P**	16.9, 0.54	[61].
8				**Available K%(mg/kg)**	138.7,	[61],[43].
9				**Fe**	182.3, 200	[61],[43]
10				**Cu**	4.04, 16.4	[61],[55]
11				**Zn**	1.91	[61]
12				**Mn**	27.3	[61].
13				**Cd**	0.74, 0.59	[61],[55]

Physico-chemical and biochemical factors

Table 2.2 compiles the arrays of physicochemical that predominantly regulate the decomposition process in earthworm and microorganism-mediated systems such as vermicomposting and composting. The alteration profiles of those attributes can also be appreciated from **table 2.3**.The majority of the studies showed that modification of physical attributes like temperature, bulk density, and water retention capacity of the feedstocks are strong indicators of the maturity of the decomposition process in addition to chemical attributes (pH, total organic C, C/N ratio, nutrient (N, P, K, Ca, Mg, etc.) availability). The ambient and reactor temperature influences earthworm activity . Earthworm generally requires a mesophilic ~ 25-40ºC temperature range (**Table 2.3**). The feedstock's bulk density and moisture content also influence the earthworm activity. Generally, a 50-70% moisture level is suitable for vermicomposting [7,30]. However, a bulk density of nearly 1-1.2 g cc-1 is favorable for vermicomposting (**Table 2.3**). Among chemical attributes, pH and the C/N ratio of the feedstock are the two most vital factors in determining the time and maturity for vermicomposting [33]. Apart from that, total organic carbon (TOC) levels, N, P, K, and metals, also play an essential role in determining the quality of the end product **(Table 2.3)**.

Table 2.3: List of some end product quality assessment of previous works

Sl. No.	Substrate/ feedstock materials	Earthworm Species	Stocking density & maturity time	Functional outcomes (End product characteristics)	Scientific Knowledge given	Reference
1	Jute mill waste (JMW), Cow Dung (CD), vegetable Waste	*Metaphire posthuma*	10 worms kg^{-1} 60 Days	i. NPK increase, ii.Earthworm count increase iii. Body weight increase iv. Cocoon count v.TOC& pH decreases vi. Humic acid, Fulvic acid vii MBC increases viii.Cr,Pb,Fe,Zn decreases ix. Bulk density decreases x.WHCincreases,MBN increases	From JMW, we can accomplish nutrient stabilization & metal remediation through vermicompost with the help of endogeic earthworm *M. posthuma*	[51] biofertilizer
2	Vegetable market waste + Rice straw + Cow Dung	*Eisenia fetida, Perionyx excavates*	10 worms kg^{-1} 60 Days	i. Bacterial count increases (*E. fetida* system) ii. TOC pH decreases iii.Available NPK increases (both E. fetida&P. excavatus)	Different N-fixing & P-Solubilizing bacterial strains are found in earthworm gut helps in formation of rich soil & crops raising in comparison with the	

3	Kitchen Waste + Paddy Straw + Cow Dung (Urine free)	*Eisenia fetida* , *Eudrilus eugeniae* ,*Perionyx excavates*	10 worms kg^{-1} 45-50 Days	i. TOC reduced ii. C/N ratio reduced iii. Compost respiration reduced iv. Coliform count reduced v. Toxic metals (Cd, Zn, Cu) reduced vi. Alkalinity reduced vii. Earthworm biomass increased viii. NPK availability increased ix.Enzyme activity increased x.Microbial growth xi.Urease activity increased xii. Humic substances increase xiii.N-fixing & P-Solubilizing bacterial population decreases xiv. Bacterial population decreased	Decomposition of biological wastes can be facilitated by using 2 or more earthworm species & it results in increment of NPK availability, enzyme activity, economically feasible.	[55].
4	MSW + CD	*Eisenia fetida*	10 worm kg^{-1} 60 days	i. N, P, K increased ii. pH decreased iii.BD increased iv.WHC decreased v.MBC increased vi. Pb, Cr & Cd accumulation efficiency of *E.fetida* increased vii. Pb, Cr, Cd are decreased	Different composting techniques are useful to reduce MSW landfills. Real field application should be done in this sector so that we can manage MSW landfills.	[15]

5	SMS + CD	*E.fetida,E.eugeniae,P. excavatus*	10 worm kg-1 60 days	i. Reduction in Crystalline index (CI) ii. MBC increases iii. Compost respiration (CR) decreases iv. pH & TOC decreases v. N, P increasesvi. Microbial count increases	Degradation of lignocellulosic biomass i.e., SMS with the help of different earthworm species can degrade the SMS & can act as increment in microbial communities & their metabolic processes	[9]
6	Paper Waste + CD	*E.fetida ,E.eugeniae*	50 worms Kg-1 30 days	i. TOC & pH decreases ii. Total N, P, K increases iii. C/N ratio decreases iv. Fe, Ni, Zn, Cr, Pb level decreases	FLUVIT (FLippable Units vermireactor Train System) is a rapid vermicompost technique which can reduce paper waste & can easily generate organic fertilizer. PVC (Paper vermicompost) act as Soil regenerator which helps in plant growth	[58]
7	Organic garbage + LARM (Leachate absorbing raw materials) i.e., Cocopith, bagasse, Jute Waste	*E.euginae ,E.fetida*	60 days		Using ASMV (aerobic Sponge Method Vermitechnology) technique, one can convert organic garbage in to vermicompost macro level	[43]

Continue…

8	SMS (Spent mushroom stock) +CD	*E.fetida,E.andrei*	40 worms kg-1,84 days	i. C/N ratio decreases,ii. pH, EC, TOC decreases,iii. Total NPK increases,	Using vermicompost technology,one can easily convert SMS to value-added materials &it can also be used in organic agriculture	[59]
9	CD + Waste corn pulp + Card board box + vegetables	*E.fetida*	1 Kg/m2 1-2 months	i. NPK increases ii. pH,TOC decreases	A constant flow through vermireactor allows addition of organic waste & very stable vermicasts which possess higher NPK compositions	[60]
10	TFCA (Tea factory coal ash) +CD	*Eisenia fetida,Lampito mauritii*	10 worms kg-1 60 days	i. pH, TOC decreased, ii. Mn, Zn, Cu, As decreased iii. Total Nitrogen increases	It demonstrates that prolonged heavy metal rich TFCA exposure has little impact on bioconversion efficiency of both the earthworms. Increase in MT levels directly indicates metal accumulation in earthworm guts.	[31]

Microbial growth and enzyme activity

The changes in microbial and enzymatic profiles could be the essential functional indicators for assessing the technical feasibility of all kinds of composting systems [9]. Villar et al. (2017) studied the microbial phospholipid fatty acid assay (PLFA)-derived microbial community profiles, fatty acid distributions, and enzyme activity in pre-composted pig manure under static conditions and vermicomposting. They stated feedstock decomposition was faster under vermicomposting than in the static maturation system. Microbial PLFA-based assessments are reliable tools for appreciating the response of microbial communities to habitat fluctuations [34]. The gut microbes initially attribute the decomposition of the solid waste, whereas the earthworm grinds the waste into finer particles [35]. Earthworm species and feedstock nature play a starring role in increasing the microbial populations and their community structures in the vermireactors [34,9]. The earthworm communal activity and their gut-associated microorganism play a key role in solid waste degradation and stabilize their nutrient availability in the treated materials. With the help of the 16S rRNA cloning technique, the diversity and abundance of gut microbes in *Eisenia fetida* and *Perionyx excavates* have been reported [23]. To study the biological index of microbial diversity in different environmental situations, phospholipid fatty acid (PLFA) profiling is done [37]. Under various situations, microbes produce PLFA to sustain the stability of the cell membrane [34].

Earthworm intestines harness numerous types of microorganisms by acting as natural incubators that provide favorable conditions for microbial augmentation [35,36,37]. However, there are contrasting interpretations regarding the characteristics of earthworm gut-associated microflora. According to Satchell (1967)[41], the earthworm gut flora seldom possesses indigenous microbial communities; instead, the intestinal microflora of earthworms harbors the communities brought along with the feed materials. On the other hand, a few studies revealed that the microbial community structure of earthworm intestines is substantially more diverse than the immediate habitat [42]. As such, the earthworm gut environment greatly facilitates microbial growth.

Interestingly, the earthworm intestine not only promotes the growth of facultative anaerobes but also greatly facilitates the aerobic microbial communities even though the oxygen level in the worm intestine is low [33]. Hussain et al. (2016)[40] identified potent plant growth-promoting bacterial strains from earthworm intestines cultured in biowaste-based vermibeds and utilized those identified strains as biofertilizer agents. A short account of bacterial diversity in earthworm-mediated systems has been schematically presented in **(Fig. 2.2.)**

Apart from the microbial diversity, earthworm intestines harness arrays of digestive enzymes (protease, lipase, cellulase, amylase, etc.), hormones, and antibiotics [40,41]. These enzymes and other biomolecules significantly expedite the mineralization of the gut-passed feed materials and accelerate the feedstock humification process when released via the worm excreta [45].Aira et al. (2007)[46] showed that microbial growth (microbial biomass C & N, microbial population, and basal respiration) and activity of vital enzymes in ready vermicompost (phosphatases, β-glucosidase, protease, etc.) substantially reduced over time after the earthworms were withdrawn; which resulted in the corresponding decrease in the nutrient concentrations.

Earthworm species, stocking density, and duration

The unique beneficial activities of surface-dwelling earthworms were identified years ago by scientists like Darwin (1837). Later, the burrowing nature of earthworms has made them helpful in accelerating the decomposition of waste materials into nutrient-rich manure, known as vermicomposting. Based on their feeding habits, earthworms could be classified into two major groups, detrivores and geophagous [47]. However, Bouch, (1977)[48] reported the most widely used classification system of earthworms is based on their habitat preference, which divides them into epigeics, anecics, and endogeic. The epigeics thrive on the surface soil, feed upon decaying organic matter, and can be named detrivores [3]. The anecics live below the soil surface, feeding on the mixture of soil and organic materials; hence, they can be named geo-phytophagous. The endogeics, on the other hand, are true geophagous (i.e., Soil feeders) living in deeper soil layers and feeding on carbon-rich soil [49]. According to a recent report, about 7000 earthworm species belong to about 700 genera and 23 families worldwide [50]. However, the epigeics (*Eisenia fetida*, *Perionyx excavate,* and *Eudrilus eugeniae*) are highly efficient for vermicomposting because they prefer to feed upon the decaying organic matter [51]. A few studies have also reported the organic matter decomposition efficiency of the anecics(e.g., *Lampito mauritii*) because they can thrive on organic matter-rich feedstock to a considerable extent [47,48]. Moreover, the effects of endogeic earthworms (e.g., *Metaphire posthuma*) on biowaste decomposition dynamics have been studied [2,[54].

Sahariah et al. (2015)[23] found that owing to their deep-burrowing habit, *M. posthuma* facilitates the humification process more than *E. fetida*.

Stocking density or the initial member of worms and earthworm species also considerably influences the end product quality and duration for attaining maturity **(Table 2.3)**. Ndegwa (2000)[55] observed that the initial stocking density of *Eisenia fetida* in biosolid-based vermibeds significantly influenced their feeding rate. Mupambwa (2016)[56];studied the effect of *Eisenia fetida* stocking density on compost maturity and end-product quality of fly ash-cow dung-waste paper-based vermibeds. Nutrient mineralization and stabilization of effluent treatment plant sludge-mediated vermicomposting system was greatly improved based on the initial population of *Eisenia fetida* [57].Previously, Garg 2008found that the incorporation of ~27-53 specimens of *Eisenia fetida* per kg feedstock resulted in efficient nutrient recovery from textile wastewater sludge. Several studies have indicated that a stocking density of about ten worms kg-1 results in satisfactory growth of *Eisenia fetida* and *Eudrilus eugeniae* in biogenic waste-based vermireactors, and high-quality vermicompost could be harvested in about two months [49,38,52,9].

Various kinds of research have been conducted on the quality stabilization of vermitechnology. Still, much effort is necessary to standardize the optimum duration regarding technological improvement [7]. External factors such as feedstock composition, temperature, earthworm species, and their initial density considerably fluctuate the maturity time of vermicomposting [58]. The optimum duration of incubation is estimated by the physico-chemical attributes, such as available NPK, C\N ratio, etc., Cabanas-Vargas etal., 2015 certify that the stability of the finished products . Abbasi et al., (2018)[59] observed that paper waste would be transformed into nutrient-rich, less toxic compost within a month (i.e., 30 days) by using a stocking density of 50 worm kg-1.In contrast, Tajbakshet al. (2018)[60] found that it took more than 80 days to spend mushroom stock into mineralized vermicompost using 40 worm kg-1 stocking density of *E. fetida* and *E. andrei*. Overall, these studies indicate that the waste decomposition efficiency of earthworms and the process duration dramatically vary depending upon their initial population.

2.2.3 Feedstock composition and quality indices

Setting up earthworm-compatible feedstock is a vital factor for the success of vermitechnology. **Table 2.4** shows some complex waste-based feedstocks used for different earthworm species-mediated vermicomposting systems. The table depicts that industrial wastes like jute loom refuge and coal ashes could be successfully vermicomposted to produce sanitized manures. Feedstock maturity, stability, and duration of the vermicomposting and composting process are closely linked, and those are the critical factor concerning the economic viability of vermitechnology [7]. Agricultural biowaste or the lignocellulose complex hetero-polymers are unfitting for animal feed as they have low protein content and are slowly subjected to microbial decay [54,55] .

Table 2.4. Waste-based feedstock composition and verified earthworm species for successful vermicomposting

Feedstock composition	Earthworm species	References
Vegetable market waste + Rice straw + Cow Dung (urine free)	*Eisenia fetida, Perionyx excavatus*	[40]
Kitchen Waste + Paddy Straw + Cow Dung (urine free)	*Eisenia fetida , Eudrilus eugeniae Perionyx excavates*	[55].
Municipality Solid Waste + Cow Dung(urine free)	*Eisenia fetida*	[61]
Paper Waste + Cow Dung(urine free)	*E.fetida , E.eugeniae*	[58]
Organic garbage + LARM (Leachate absorbing raw materials) i.e., Cocopith, bagasse, Jute Waste	*E.eugeniae , E.fetida*	[43]
CD + Waste corn pulp + Card board box + vegetables	*E.fetida*	[69].
TFCA (Tea factory coal ash) +CD	*Eiseniafetida, Lampitomauritii*	[50]
Jute mill waste (JMW), Cow Dung (CD), vegetable Waste	*Metaphireposthuma*	[51]

Various researchers have reported the efficiency of vermitechnology using different earthworm species in organic waste and lignocellulosic biowaste, as shown in **Table 2.5.** Vegetable waste and lignocellulosic waste like paddy straw could be successfully converted into value-added organic fertilizers within 45-50 days using 2-3 earthworm species in combination [7]. A 1:1:1 mixture of vegetable market waste, paddy straw, and cow dung not only resulted in high-quality end products but also facilitated the worker in depriving useful biofertilizer inoculums of *Eisenia fetida* gut [40]. For an economic study of vermitechnology and aerobic composting, various appropriate tools have been developed to improve the composting duration and physic-chemical parameters [56,57] . Hussain et al. (2016; 2018)[40,[7] proposed a Compost quality quotient (CQQ) equation that incorporates the changes in all the vital parameters within a specific duration of composting and vermicomposting. Adding some weighing factors for each index, CI (Clean Index) helps determine the level of occurrence of any metals or the elements in the processed materials; the values indicate the upper limit of such occurrences. The FI facilitates determining the value of compost respiration regarding soil productivity change. Apart from these, the C/N ratio, microbial quotient, and microbial metabolic quotient are effective indicators for maturity determination for biocomposting processes [9].

On the other hand, indicators such as crystallinity index (CI) and humification index (HI) help in determining the maturity time of the feedstock based on the rate of transforming crystalline materials to an amorphous state; [32]. In particular, the CI helps evaluate the decomposition process based on the crystalline materials' transformation rate to amorphous states. However, this index is expensive and, to some extent, inaccessible to small entrepreneurs.

Table 2.5: Vermicomposting of different biogenic and lignocellulosic feedstocks using different earthworm species

SI No	Feedstocks	Most dependable epigeic species	References
	(A) Lignocellulosic waste		
1	Water hyacinth	*Eisenia fetida*	[65]
2	Apple pomace	*Eisenia fetida*	[66]
3	Oil palm	*Eudrilus eugeniae*	[11]
4	Market waste (Vegetable) and rice straw mixture	*Eisenia fetida*	[40]
	(B) Organic waste		
5	Paper waste (Non-recyclable)	*Eisenia fetida*	[67]
6	Pig manure	*Eisenia fetida*	[51]
7	Industrial waste (Cotton)	*Eisenia fetida*	[68]
8	Vegetable and Industrial waste	*Eudrilus eugeniae*	[69]

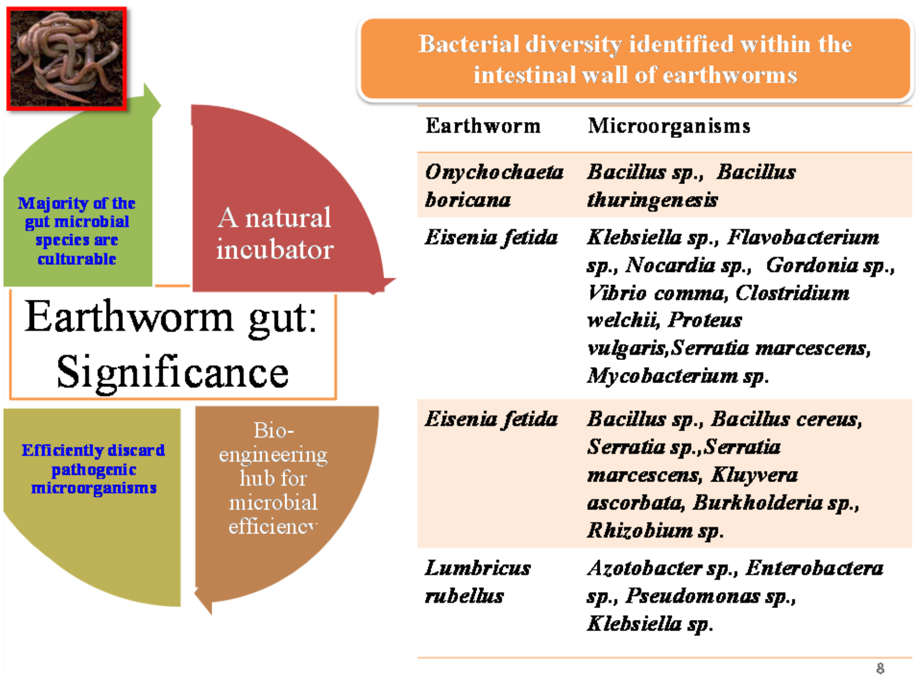

Fig 2.2: Bacterial diversity identified within the intestinal wall of earthworms

Pollutants and their detoxification: A focus on polycyclic aromatic hydrocarbons (PAH)

Vermitechnology is the most practiced bioconversion technique compared to aerobic composting [69,24]. Bhattacharya and Kim, (2016)[71] reported that earthworms could survive, flourish, and detoxify metals (Cd, Cr, Pb, etc.) in contaminated soil and solid wastes [4]. Metallothioneins, low molecular weight proteins, are believed to be readily induced in the intestines of metal-exposed earthworms [47,29]. These proteins form organometallic complexes via the thiol-group binding mechanism and transport the metals in bound forms to chloragogenous tissues, where they are neutralized [72].

The organic pollutants are released in the soil from the incomplete combustion of coal and petroleum. The deposition rate of PAHs in the soil is generally high due to their high hydrophobicity and low solubility [73]. Sisinno et al. (2003)[74] reported a significant occurrence of quite a few PAHs (benzo[a]anthracence, benzo[a]fluoranthene, benzo[a]pyrene, fluoranthene, chrysene, etc.) in the solid waste samples of Poland. Recently, Guo et al. (2020)[76] found all 16 priority PAHs in urban yard trash in the range of 0.38 to 14.0 mg kg-1. PAHs are also found in the residues from MSW incineration units in the UK [77]. **Fig. 2.3** schematically explains the source and deposition profiles of organic pollutants like PAH in the environment. Hickman and Reid, (2008)[23] reported that for the remediation of various organic and industrial wastes into mineralized form, earthworms are widely used as earthworm has the property of bioaccumulation. Species like *Eisenia fetida*, *Eisenia tetraedra*, *Lumbricus terrestris*, and *Aporrectodea caliginosa*can potentially remove organic micro-pollutants like PAHs from soil (Sinha et al.)[78]. Various organic pollutants in the soil, such as PAH, have been readily accumulated by earthworms [76,77].

Several earthworm species have shown various PAH accumulation patterns *Eisenia fetida* [81], *Apporrectodea caliginosa* [39], *Amynthus gracilis* [82], and *Lumbricus rubellus*[83].Ma et al. [1995][84] reported that earthworms expedite the degradation of organic contaminants like phthalate, phenanthrene, and fluoranthene in soil. Various bacteria and fungi have the potential to degrade some chemicals, such as hydrocarbons. The earthworm gut microbes can accumulate micro-pollutants from the soil during food uptake [85]. The combined action of autochthonous micro-organisms and earthworms increases the biodegradation of hydrocarbons by stimulating microbial activity [82- [88]. Eijsackers et al., (2001)[78] also reported mutual involvement between earthworms and micro-organisms that facilitated the removal of PAHs from contaminated feedstocks. The mutual association of earthworms and their gut-associated microorganisms convert complex mineralized waste into nutrient-rich products [89]; and thus plays a vital role in metal removal from organic pollutants and consequently takes part in the detoxification pattern of mineralization in vermicomposting [90]. Earthworms also excrete various enzymes like amylase, lipase, cellulose, and chitinase to help break down organic matter in the soil and thus help in degrading the organic pollutants in the soil[79]. **Table2. 6** showcases the outcomes of some PAH removal studies employing earthworms. These studies indicate that PAH remediation pathways and the budget for removal through biological processes need to be assessed mechanistically.

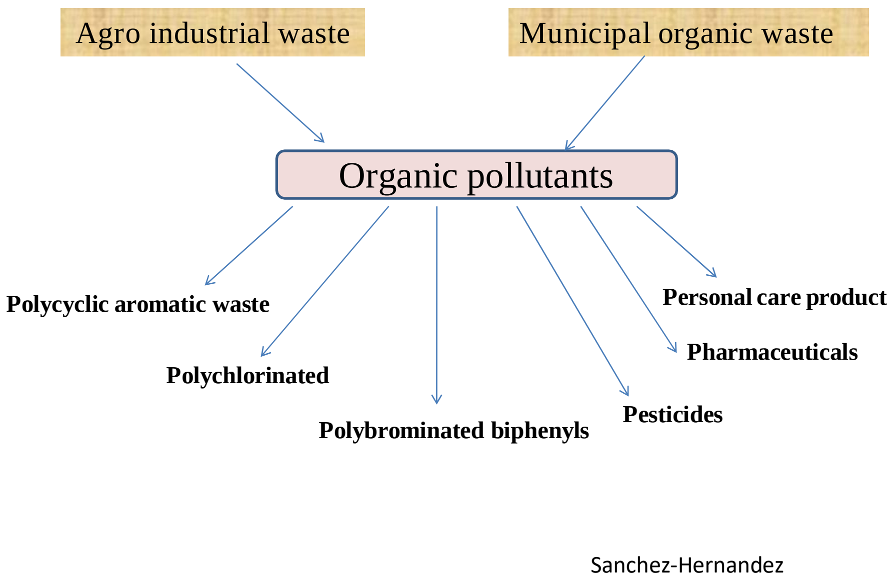

Fig2. 3: The sources of organic pollutants in the environment

Table 2.6: Different treatments used for PAH removal from different sources

SI	PAH compound	Source	Level of occurrence	Treatments used	Refences
1	Phenanthrene (Phen), Anthracean (Anth), Benzo(a)Pyrene (BaP)	Sewage sludge	>96% for Phen, >99% for Anth and >97% for BaP.	Vermicomposting*(Eisenia fetida)*	[91]
2	Biphenyl Benzo(a) Pyrene , Dibenzo(a,h)anthracean	Contaminated Soil	1.62–2.40 mg/kg	Vermicomposting*(Eisenia fetida)*	[47]
3	Phenanthrene (Phen), Anthracene (Anth), Benzo(a)Pyrene (BaP)	Sludge (Wastewater treatments plant)	96% Phen, 99% Anthra and 97% BaP	Vermicomposting*(Eisenia fetida)*	[79]
4	PAH (Lipophilic organic micropollutants)	Soil(gas works site)	11,820 mg/kg	Vermicomposting(*Eisenia fetida, Eisenia tetraedra, Lumbricusterrestris, Lumbricusrubellus)*	[78]
5	Coal	Brick Kiln industry	1-1.5 tonnes of BKCA (brick kiln coal ash)per day	Vermicomposting*(Eisenia fetida)*	[18]
6	Coal Ash	Tea factory		Vermicomposting *(Eisenia fetida, Lumbricusrubellus)*	[92]
7	16 PAH compounds	Contaminated soil		Microbial *(Bacteria , fungi)*	[93]
8	Pyrene			*Mycobacterium vanbaalenii* PYR-1	[94]

Innovation vermireactors and vermicomposting process

The profound metabolic and reproductive ability permits the earthworm to survive in a fluctuating environment. In the vermireactors, the earthworms prodigiously crawl, consume the feed materials, and pulverize them into finer particles. In due course, the earthworm gut microbes degrade the feed materials, releasing various active microflora and a wide range of enzymes from the worm excreta [4]. A vermicompost reactor is a device that facilitates the vermicomposting process by providing the optimal conditions required for earthworms to live.However, the waste valorization potential of earthworms may fluctuate depending on the reactor size and shape. Abbasi et al. (2018)[59] stated that about 20 kg capacity of vermireactor facilitates the speed of waste decomposition. While Goswami et al. (2014)[31] found that a truncated cone-shaped reactor with perforated walls was satisfactory for maintaining aeration and performing earthworm activity. Abbasi et al., (2009)[29] define vermicomposts as amenable to continuously-fed operation, whereas compost is an essential batch process. The biochemical and microbial processes have numerous significant differences [91]. Vermicast production is considered the most reasonable and easily significant vermicomposting system. It is humus and plant-friendly [92-94].Abbasi and Ramasamy, (2001)[94] reported that earthworm takes 6-18h to form vermicast based on earthworm species and the substrate nature. The conventional vermireactors take almost 80-90 days to form vermicast.

In an interesting study, Ghorbani et.al (2021)[95] reported a design of a smart close reactor for vermicomposting. The study concluded that odorous solid waste (e.g., sewage sludge) could be more efficiently vermicomposted in the innovated reactor than traditionally used reactor; in particular for temperate climatic conditions. Previously, Manyuchi.et.al (2013)[96] also developed a continuous flow through vermireactors that efficiently converted more ~7000kg of organic waste into nutrient reach vermicomposts. However, mechanized vermicomposting system with upgradable features that suits for household level waste recycling facilities have not been developed so far. This can be indeed a new an interesting domine to work.

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