CHAPTER-2

Review of Literature

2.1 Introduction

Vermicomposting, an action that necessitates the fragmentation of bio-waste materials using earthworms, has turned out to be an environmentally favorable approach for recovering waste while simultaneously enriching the soil with organic matter and nutrients. Several types of research have exhibited the beneficial repercussions of waste vermicompost on SOC sequestration in arable lands. Liu et al. (2019) [1] carried out research work in China and established the fact that vermicompost application significantly increased SOC content in the soil, indicating its potential for carbon sequestration. Additionally, the study highlighted the vitality of earthworm activity for rapid decomposition of obstinate biological residues there by releasing soluble carbon compounds in soil [1]. Investigating the effects of vermicompost application on the quality of Mediterranean agricultural soils Domínguez et al. (2018) [2] found that vermicompost application significantly increased SOC levels, attributed to enhanced microbial activity and organic matter decomposition facilitated by earthworms. The study also emphasized the importance of vermicompost as a tool for increasing SOC sequestration in arable lands. In addition to carbon sequestration, waste vermicompost offers numerous benefits for soil health in arable lands. A pervious study reported the significant beneficial role of vermicompost application as soil fertility stimulants that also eventually enhance productivity and quality of vegetable crops [3]. They observed considerable improvements in soil structure, the capacity to retain water, and nutrient availability following vermicompost application. These enhancements were attributed to the organic matter content and microbial activities promoted by vermicompost, leading to the improvement in soil fertility and overall soil health [3]. While waste vermicompost demonstrates the potential for SOC sequestration and soil health improvement, certain challenges and limitations need to be considered. Suthar (2016) [4] emphasized the importance of using high-quality vermicompost derived from appropriate organic waste sources to ensure optimal nutrient availability and minimize the presence of contaminants. Furthermore, careful management of earthworm populations, optimal application rates, and considering the long-term stability of sequestered carbon are crucial aspects that require further investigation [4]. To fully understand and harness the potential of waste vermicompost for SOC sequestration in arable lands, field-based long-term research is essential to appreciate the sustenance of the sequestered SOC, its susceptibility to loss through erosion or leaching, and its mobility in the plant-soil interfaces. Wang et al. (2018) [5] emphasized the importance of continuous monitoring to evaluate the dynamics of carbon sequestration and assess the impact on crop yield and quality. Additionally, integrated studies investigating the synergies between vermicompost and other carbon sequestration strategies, such as cover cropping and conservation tillage, would contribute to developing sustainable soil management practices [5].

Waste vermicompost shows promise as a valuable approach for promoting SOC sequestration and improving soil health in arable lands. Scientific studies have highlighted its potential benefits, including increased SOC content and improved soil properties. However, addressing challenges related to sourcing high-quality vermicompost and optimizing application practices is crucial. Further research and monitoring are needed to refine techniques, assess long-term carbon stability, and explore integrated soil management practices for maximizing the benefits of waste vermicompost in sustainable agriculture and climate change mitigation. The current review focuses on several vital aspects related to applicability of waste vermicompost towards sustainable recycling of natural resources.

2.2 Solid waste and vermicomposting

One of the most alarming issues for the modern-day world is the management of solid waste. Rapid population growth, urbanization, and industrialization have led to widespread production of solid waste. Reduction, sorting, reuse, and recycling of waste are a few suitable options. However, a huge quantity of solid waste is dumped into the surroundings without any pre-treatment which in turn causes several environmental impacts. Although, several approaches for the management of wastes such as landfill, combustion, incineration, etc., have been proposed but the feasibility of these techniques is questionable because of the technical sophistication and high cost involved. On the other hand, vermicomposting is a sustainable and economically viable biotechnological method where earthworms by the virtue of gut microbes, enzymes secreted, and metal-binding protein convert the toxic wastes to value-added fertilizer. The microbes help in the process of mortification whereas the byproducts like the enzymes that are produced in the process help in breaking down the aggregated compounds into much simpler ones. In this chapter, we will try to understand how vermicomposting acts for the management and mitigation of organic waste. First, let us understand the global waste generation scenario.

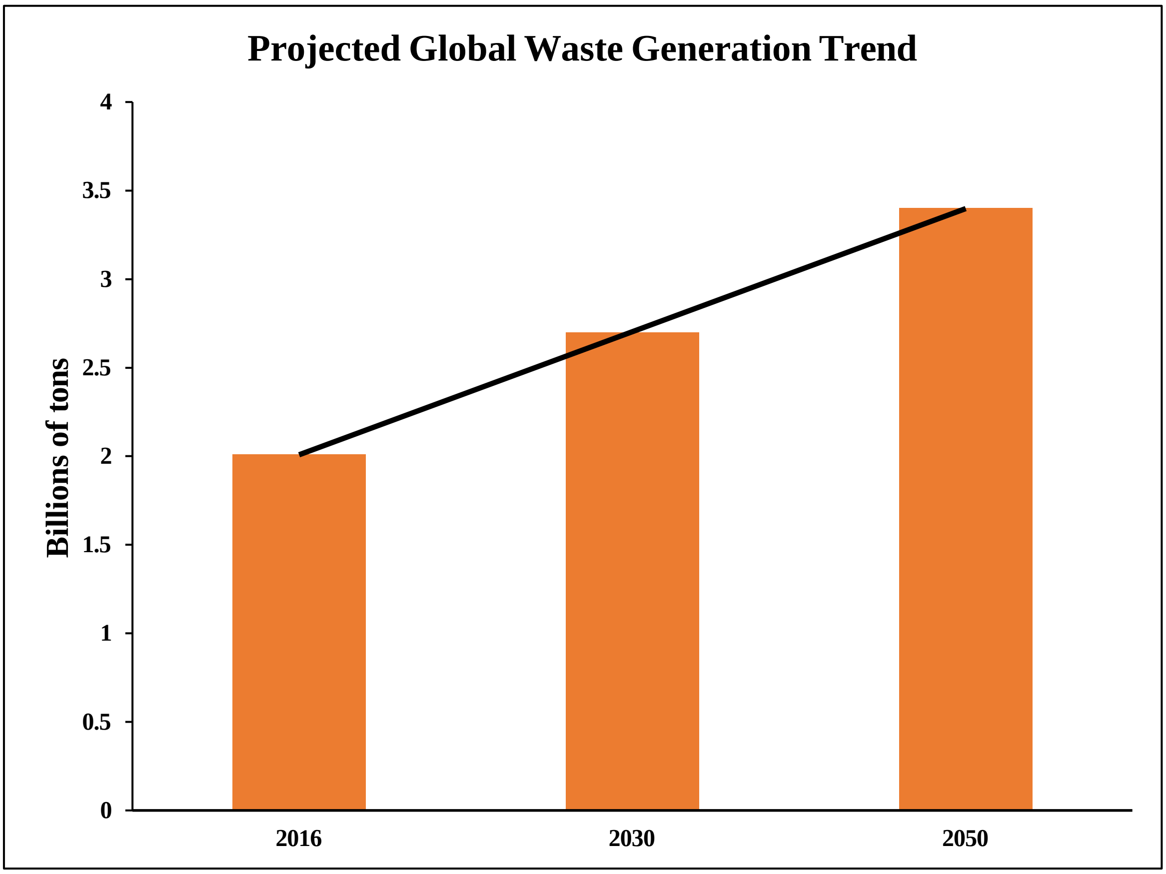

Fig. 2.1: Projected Global waste generation

Global waste generation is increasing rapidly with time Fig. 2.1. Most of the waste generated is dumped into the surrounding environment without any prior treatment. Global municipal waste produced annually is about 2.01 billion tons, which would likely increase up to 3.4 billion tons over next few decades [6]. Only 33 percent of the total waste generated is not controlled in a secure environment-friendly approach [7]. An average single individual generates about 0.11 to 4.54 kg per day of waste [8]. Around 34 percent of global waste is generated by high-income countries comprising only 16 percent of the total global population [7]. Comparatively high-income countries generate wastes at a very lower rate than that of low-income countries and this data is very much increasing day by day [9]. Thus, a three-times increment in total waste generation is expected in low-income countries till 2050 [10].

Several waste management technologies are adopted around the world, but these techniques have several impacts on environment and economy Table 2.1.

Table 2.1: Waste management technologies and their impact

SWM technologies	Effect on economy	Effect on environment	Reference
Landfill	High operational cost	Oduor, air pollution, ground water and run-off pollution	[11]
Incineration	High operational cost, thermal energy production	Air emissions, bottom ash and Fly ash	[12]
Pyrolysis	High operational cost, crude oil i.e. Char and liquid fuel production	Plastic degradation only, air pollutions	[13]
Anaerobic digestion	High operational cost, bioenergy (Methane) production	Degrade organic wastes, GHG emissions decreased	[14]
Composting	Low operational cost Organic fertilizers production	Biodegradable organic waste only. Heavy metal is not reduced	[15]
Vermicomposting	Low operational cost, Organic fertilizers production	Heavy metals are minimized and fragmentation of organic waste using earthworms	[16,17]

Considering other waste disposal techniques, the advantages of using vermitechnology is far better. Other techniques related to the management of waste technologies involve a high operational cost and need skilled operators. Whereas aerobic compositing is economically viable, but the presence of heavy metal obstructs the process of decomposition. On the other hand, vermicomposting is a well-known efficient process used for extracting and refining (metal remediation) industrial waste [18,19].

A comparative study between vermicomposting and conventional composting elaborated that vermitechnology helps to reduce the number of heavy metals, enriching the end-product into valuable fertilizer with high nutrient value, which substitutes chemical fertilization to a considerable extent thereby curtailing the environmental pollution [20]. Hence, it imperative to adopt progressive techniques like composting and vermicomposting that involve energy out of the waste process rather than the usual waste recycling techniques.

2.2.1 Recycling of waste through vermicompost

Earthworms have played a significant part in maintaining the quality of soil by recycling bio-waste since ancient times. Vermicomposting is a simple biotechnological method of preparing compost with the help of earthworms. While some categories of earthworms are used for efficient bioconversion and enhancement of the whole process. Earthworms consume organic materials, digest them, and excrete them in the form of small granules, these fine granules are together known as vermicompost. The vermicompost has high nutrient content (NPK), high porosity, permit air circulation, contain diverse microbial communities, plant growth regulators, and retain water more efficiently than traditional composts [21].

2.2.2 Earthworm species suitable for vermicomposting

Earthworm species that are voracious feeders, prolific breeders, have a short life span, less mortality rate, and excrete greater quality vermicast are generally used for vermicomposting. Details of some of the most suitable species of earthworm for vermicomposting are listed with necessary details in Table 2.2.

Table 2.2: An account of earthworm species prescribed for vermicomposting

Earthworm species	Ecological category	Niche	Color	Viability* (in %)	Lifespan (days)	Tolerance level	Reference
Eisenia fetida	Epigeic	> Live in the sub-surface soil layer	Brown with distinct bands	73 to 80	45 to 51	Very high	[22]
Eudrilus eugeniae		> Drill temporary vertical burrows	Reddish brown	75 to 84	50 to 70	Medium	[23]
Perionyx excavatus		> Feed on decomposed organic matter	Royal purple	~90	40 to 50	Medium	[24,25]
Drawida nepalensis	Endogeic	>Build horizontal permanent burrows >Dwell in the deeper soil horizon >Feed on mineral soil and soil organic matter	Pale yellow	75 to 85	100 to 120	Medium	[24,25]
Aporrectodea calignosa			Pale pink	91 to 95	120 to 150	Low	[24,25]
Lampito mauritii	Anecic	>Thrive on the soil surface >Make permanent burrows on the soil surface >Feed on leaf litter and other organic debris	Grayish to light brown	~98	100 to 105	Low	[24,25]
Lumbricus rubellus			Reddish brown	60 to 70	120 to 170	Low	[24,25]

2.2.3 Conditions required for vermicomposting

a. Ambience-Earthworms require a cool, shaded place with high humidity for proper functioning. Since earthworms are nocturnal it is essential to provide shade to vermicomposting beds. Earthworms multiply well in pits or beds filled with readymade food. Proper mixing and turning need to be done from time to time to ensure aeration.

b. Moisture- Adequate moisture conditions (70-90%) must be maintained in the vermibeds for the proper functioning of the earthworms. Around 85% of the earthworm's body consists of water. They respire through the body wall, so it is kept moist through constant release of mucus through the dorsal pore. Lack of moisture causes dehydration whereas excess moisture can cause anaerobic situations.

c. Temperature- 20 to 35^{o}C is the adequate temperature range for proper functioning of the earthworms. Temperature above 45^{o}C or below 40^{o}C is not favorable. Extremely high temperature causes dehydration whereas cessation of activity occurs at extremely low temperature.

d. pH- Feeding material with pH 6.0 to 8.5 is adequate. The earthworm fecundity is severely affected at pH below 4 and above 9. To get an ideal pH green matter must be added to the vermibeds along with dry biomass.

e. Pre/Partially digested feed (organic biomass)-The organic biomass must be pre-digested before using it as a feed for earthworms. Any biomass generates heat during initial decomposition, and we know that earthworms do not function well at extremely high temperatures. So, the biomass needs to be pre-digested before using it as feed.

2.2.4 Mechanism of organic waste degradation and caste production by Earthworm

Vermicomposting is a biotechnological method where earthworms and their gut microbes together act to convert the organic wastes to value added fertilizer. The process of decomposition generally involves two steps. Firstly, the larger organic particles are broken down into smaller ones in the gizzard of the earthworm by muscular action. Eventually, the smaller particles with larger surface area are acted upon by the gut microbes. The effectiveness of the waste processing largely relies upon the microbial community and the characteristics of the waste [26]. Rapid decomposition of organic materials (cellulose, lignin, hemicellulose, starch, etc.) is possible because several enzymes (urease, dehydrogenase, phosphatase, protease, amylase, lipase, cellulases, etc.) are secreted by earthworms and their gut-associated microbes [27,28].

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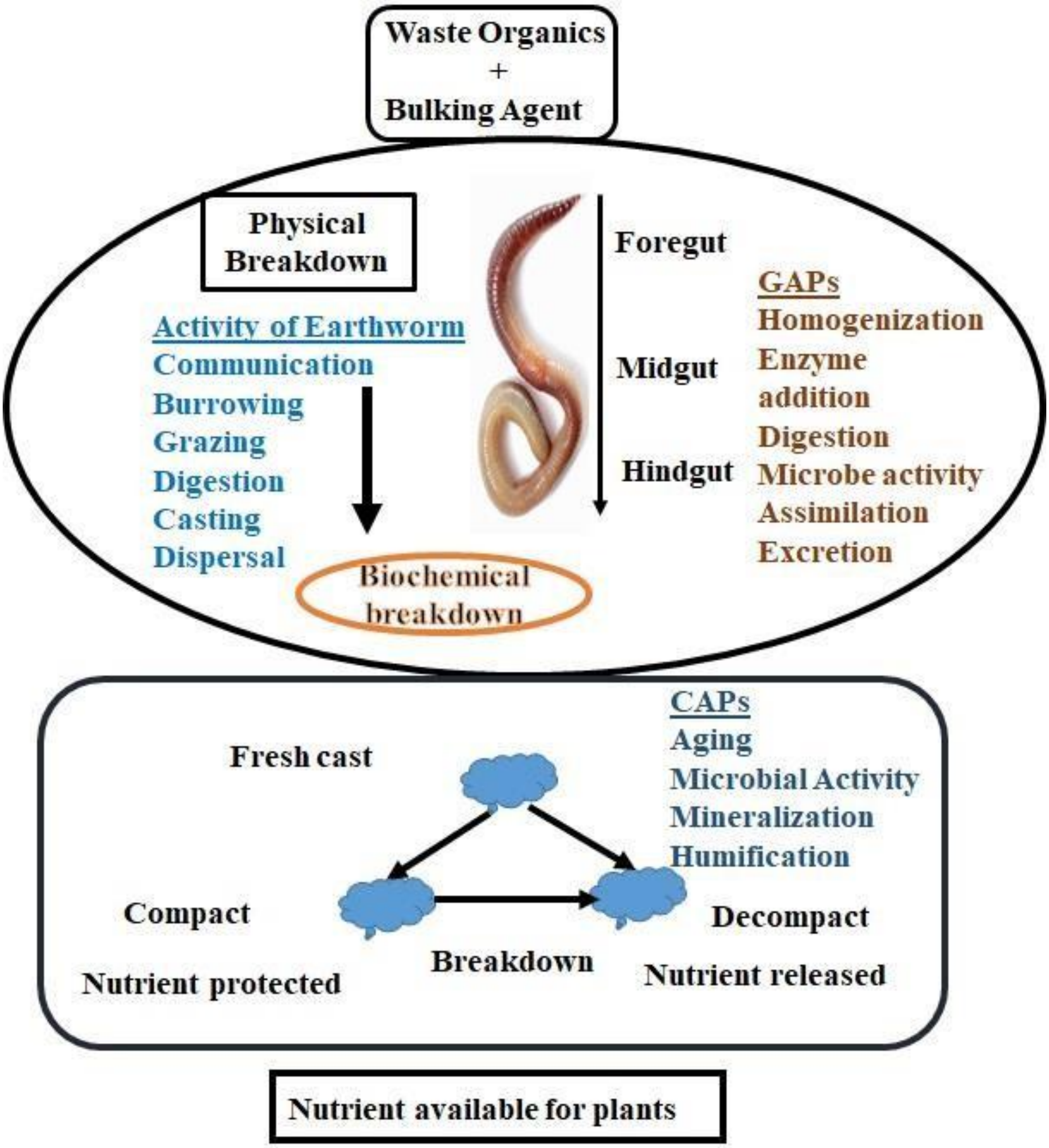

Fig. 2.2: Process of degradation and cast production by earthworm (reproduced from Samal et al. 2019 [29] with permission)

Two phases are involved in the waste decomposition process under vermicomposting, a) worm-associated processes (WAPs) and b) vermicast-associated processes (VAPs) (Fig. 2.2). The WAPs involves the interactions of the microbial communities harbored in earthworm intestines with the grinded feed materials. Eventually, the partially degraded materials are released in the vermireactors through the excretion routes of the worm (i.e., VAPs) and correspondingly the excreted materials are further degraded by the cast-released microorganisms and their enzymes thereby, stabilizing the materials as humified granular solids enriched with nutrients, active microbes, and substantially low in pollutant load [30].

2.2.5 Suitability of organic waste for vermi remediation

Several agricultural and industrial organic wastes have been recycled using vermicomposting to date. For example, silk-processing industry sludge [18], tea industry coal ash [31], dye sludge [32], sugar factory waste [33], etc. Earthworms alter physical nature of the waste-based feedstocks owing to their feeding habits and crawling movement in the vermibeds thereby substantially leading to accelerate the mineralization process, which can be assessed by the reduction rates of C/N ratio, increment in elemental bioavailability, and removal of reduces heavy metals [34,35,36]. Table 2.3 represents some of the wastes that have been successfully remediated through vermicomposting. Table 2.3 also gives an account of the earthworm species, duration, and other salient features of the studies.

Table 2.3: Vermicomposting of several Industrial waste

Waste types	Earthworm	Period	Salient features	References
Silk processing refuges	*Eisenia fetida & Eudrilus eugeniae*	60 days	More than 10 times reduction in concentrations of Cd, Cr, Pb and Zn in the end-product with concurrent increment in bioaccumulation by the earthworms.	[18]
Tea Factory Ash	*Eisenia fetida & Lampito mauritii*	60 days	Significant reduction of toxic elements (As, Cu, and Zn) was evidenced after vermicomposting.	[31]
Sugarcane industry waste	*Eisenia fetida*	105 days	Several fold rise in NPK with eventual decrease in pH, OC, and toxic elements signified waste	[33]

(Bagasse) and cattle dung			valorization potential of vermicomposting.	
Dye industry sludge	*Perionyx excavatus*	45 days	The levels of K, P, Mg, Ca, Cu, Fe, and Mn were higher in vermicomposted dye sludge compared to the control (i.e., aerobic composting).	[32]
Fruit processing waste	*Eisenia fetida*	135 days	The vermicomposted material was higher in nutrient value as compared to composting.	[37]
Jute loom waste	*Metaphire posthuma*	60 days	Decrease in organic C, pH, and metal contents were evidenced; NPK, humic substances and microbial biomass increased upon vermicomposting.	[38]
Press-mud sludge	*Eisenia fetida*	135 days	Mortality of earthworm was lowest and earthworm biomass was significantly high in 25:75 press-mud-cow dung feed-mixture compared to other combinations.	[39]
Herbal Pharmaceutical Industry waste	*Eudrilus eugeniae*	78 days	Earthworms efficiently transformed organically bound N, P, and K from the waste into bioavailable forms through release of microbe and gut-associated enzymes.	[40]
Food industry sludge	*Eisenia fetida*	90 days	Survival of earthworms was considerably challenged in unable to survive in vermibeds made up of 100% sludge and 60-70% biogas slurry	[41]
Powe plant Fly ash	*Eisenia fetida*	1 week	The ash-fixed nutrients like P and K were extracted into bioavailable forms in presence of earthworms and the increase in microbial activity	[42]
Tannery sludge	*Eudrilus eugeniae*	25days	Earthworms contributed to waste valorization by elevating phytohormone contents and microbial diversity in the finished product.	[43]
Leather industry refuge	*Eisenia fetida*	135 days	Vermicomposting resulted in enhancement in humic substances and bio stimulants in the ready vermicompost.	[44]
Petroleum industry waste contaminated soil	*Eisenia fetida*	56 days	E. fetida detoxified and neutralized toxic and hazardous materials and elements.	[45]

Brick kiln ash	*Eisenia fetida*	60 days	Significant bioaccumulation capacity of *Eisenia fetida* for toxic metals which in turn substantially sanitized brick kiln coal ashes	[46]

In most cases, a reduction of hazardous elements with concurrent increment in bioavailability of essential elements were observed. Hence, vermicomposting is a suitable option for waste-to-wealth conversion.

2.2.6 Significance

Recent studies have demonstrated that waste vermicompost application enhances crop yield and soil productivity to large extent [47,48]. As such, soil incorporation of vermicomposted waste considerably improves soil physical (aeration, structure, bulk density, and water retention capacity) and chemical (pH, cation exchange capacity, and mineralized fractions of essential elements) properties. The soil-incorporated vermicompost are not readily washed out from the rhizosphere region of soils like synthetic fertilizers due to predominance of humified organic constituents and mucilaginous substances excreted by the worm [49]. Soil incorporation of vermicompost promotes soil health through elevated microbial activity, enhancing abundance of plant growth promoting microbial communities (e.g., N-fixing, P-solubilizing, cellulose decomposing microbes, etc.), releasing plant growth hormones (auxins, gibberellins, etc.), and improving soil physical composition [50]. As such, the skill of vermicompost preparation from waste materials may open new avenue for livelihood generation for poor rural communities.

2.3 Vermicompost – A warehouse of microbial resources

Vermicomposting is an aerobic and rapid waste valorization technique governed by conjoint action of earthworms and their gut-released microorganisms [51]. Earthworms having wide adaptability to extreme conditions can transform complex waste materials into nutrient-rich organic fertilizers with abundance of bioactive microbial communities, enzymes, and effective biomolecules [52]. The diversified microorganisms (bacteria, fungi, protozoa, and nematodes) in the vermicompost efficiently contribute to disease eradication along with plant growth enhancement [53]. These microorganisms play crucial roles in soil health by promoting nutrient cycling, suppressing plant pathogens, and enhancing plant growth. In general, various factors like nature of feed-mixtures, rearing conditions (i.e., temperature, moisture, aeration, feedstock churning frequency, etc.), earthworm species, and their feedstock compatibility determine the microbial community structure in the finished vermicompost [54]. Bacteria, the most abundant microbial group in vermicompost, are involved in the mineralization of nutrients, converting complex organic compounds into bioavailable mineral forms that can be readily translocated from rhizospheric soil to plants [55,56]. The fungal communities in vermicompost contribute to breakdown of lignocellulosic materials by releasing specific enzymes that dismantle the complex polymeric frameworks [57]. On the other hand, protozoa and nematodes in vermicompost largely contribute to disease suppression by feeding on plant-pathogenic communities and release of antioxidants [40,55,58]. For instance, Atiyeh et al. (2002) [59] reported that vermicompost incorporation in soil significantly inhibited the proliferation of various plant pathogens, including *Fusarium spp*., *Phytophthora spp*., and *Pythium spp.*

The major significance of the vermicompost-based microbial resources lies to their applicability in agriculture as soil health and plant growth promoters. Hussain et al. (2016) [60] could isolate potent bacterial strains that showed promising plant growth promotional traits (N-fixation and P-solubilization). Moreover, efficient cellulolytic bacterial species were isolated from wasted paper-cup-based vermicomposting systems [61]. A recent interesting finding suggests that green waste-based vermicomposting systems can be effective sources of various actinomycetes strains that showed diverse plant growth promotional traits (siderophore production, chitinase, glucosidase, and cellulase release, etc.); thereby augmenting the rice productivity [62]. In addition to its potential applications in agriculture, vermicompost has also been explored for use in bioremediation of contaminated soils. For example, vermicompost has been shown to enhance the PAHs degradation in contaminated soils and improve soil health [35,63]. A few useful aspects of vermicompost-aided microbial diversity are discussed in the following subsections.

2.3.1. Microbes for energy

In recent years, microbe-mediated energy production from biosolids gained considerable attention in the fields of biotechnology and environmental engineering. In this context the pathways for energy generation from wasted biomass can greatly contribute to balance the energy demand supply chain in sustainable manner. According to International Energy Agency (IEA) biomass is currently the dominant renewable energy source (www.ieabioenergy.com). Microbial energy production involves the use of microorganisms to generate energy from organic and inorganic compounds. Microorganisms can produce energy through two main mechanisms: fermentation and respiration. Fermentation is the process that involves anaerobic microorganisms generate ethanol and lactic acid from organic compounds thereby, releasing energy in the process. Respiration, on the other hand, is the process in which microorganisms use inorganic compounds such as oxygen or sulfate as electron acceptors, releasing energy through the transfer of electrons [64]. Eventually microorganism mediated enzymatic conversion of sugars to ethanol has gained substantial attention of Scientific communities in recent time [65, 66, 67]. Conventionally, bioethanol production from lignocellulosic biomass includes steps like: (1) pre-treatment for fortification of cellulosic substances; (2) derivation of fermentable sugars through enzymatic hydrolysis; (3) production of bioethanol from sugars; and (4) distillation for enhancing ethanol purity [68].

Microorganisms can also be used to produce biogas (i.e., mixed gases mainly composed of methane and carbon dioxide) through anaerobic digestion; the produced gas can be effectively used for meeting household demands of energy (e.g., heating, cooking, electricity generation, etc.) thereby saving the fossil fuels to a considerable extent [69]. Microorganisms have also been used to produce electricity by developing microbial fuel-cells (MFCs). MFCs, formed by involving several microorganisms (e.g., bacteria, archaea, and fungi) produce electricity from chemical sources by oxidizing organic matter at the anode, releasing electrons that are transferred to the cathode through an external circuit, generating electricity in the process [70]. In addition to biofuels and electricity, microorganisms can also be used to produce hydrogen gas. The process of microbe-mediated hydrogen generation, technically termed as dark fermentation, which involves producing hydrogen from biomass by activating specific bacterial strains such as *Clostridium* and *Rhodobacter* [69].

Despite the potential of microbes for energy production, there are vital drawbacks of these technologies that require serious attention [69]. One of such drawbacks is the difficulty in optimization of microbial processes for energy production due to high sensitivity towards regulating attributes like pH, temperature, and substrate availability [64]. Another challenge is the selection and optimization of microorganisms with desirable properties for energy production. The microbial community involved in energy production is diverse and complex. Therefore, the identification and selection of microorganisms with desirable properties can be challenging. The use of advanced technologies such as metagenomics and transcriptomics can aid in the identification and selection of microorganisms with desirable properties [70]. In addition to the challenges, there are several future directions in the field of microbes for energy. For example, lignocellulosic biomass is a potential source of biofuel as it is abundant and does not compete with food crops [71]. However, the conversion of lignocellulosic biomass into biofuels is challenging due to its complex structure. Therefore, the development of microbial processes that can efficiently convert lignocellulosic biomass into biofuels is an important future direction [69]. Another future direction is the integration of microbial energy production with wastewater treatment. Microbial energy production can also improve the efficiency of wastewater treatment by removing pollutants and producing energy simultaneously [64]. Overall, it can be postulated that microbes have emerged as a promising solution for sustainable energy production. Future directions in the field of microbes for energy include process optimization through in-depth research on species-feedstock interactions and stabilization of reactor conditions.

2.3.2. Microbes for resource recovery

The pace of nutrient cycling in terrestrial ecosystems largely depends on diversity and activity soil-borne microorganisms. The utilization of microbial communities for resource recovery from waste streams has the potential to provide realizable solution of the environmental problems owing to exponentially increasing solid wastes [72]. The resource recovery can be referred to the processes that exert essential nutrients and plant growth promoting biomolecules from waste materials thereby converting the waste to wealth [73]. The earthworms commonly used for waste valorization through vermicomposting are voracious feeder and thus they feed upon everything in the vermicompost, eventually the ingested materials are crushed into tiny pieces by the gizzards after being chemo-stabilized via the calciferous glands, and introduced to the worm intestines, where highly diverse microbial groups and their extracellular bioactive molecules are nurtured under the protective casing of the cylindrical and segmented gut [23]. Hence, the earthworm intestines are rich and ready source of enormous beneficial microorganisms and bioactive compounds and therefore, several researchers have isolated and utilized microbial strains of various beneficial properties from earthworm gut since a long time [60,74,75,76].

Earthworm intestines have been reported to harbor useful soil growth enhancing aerobic bacterial species (e.g., *Klebsiella*, *Pseudomonas*, *Rhizobium*, *Azotobacter*, *Serratia*, *Aeromonas*, *Bacillus*, and *Enterobacter*) despite the gut environment is largely anoxic in nature [23,77]. The microbial groups commonly found in earthworm guts can be classified as plant growth stimulators, N-fixing agents, P & K solubilizing agents, and biocontrol agents. Nitrogen being an integral constituent of amino acids vis-à-vis proteins and chlorophylls is one of most vital limiting growth factors for the sustenance of plant life. As the atmospheric N is inert in its character, the plants solely depend on soil for meeting up the N-demand [78]. In this context, N fixing microorganisms are the only known living entities that can trap the abundant N-reserve of the atmosphere by converting the gaseous N to bioavailable ammoniacal N-form [79]. However, the problem of P and K availability is different to that of the N; soil is the only source of these nutrients where the assimilable forms of P and K are often chemically fixed in insoluble forms [78]. Interestingly, a few microbial communities can certain groups of microbes can revert the insoluble P and K back to soluble (i.e., assimilable) states by modifying the immediate chemical environments [78], commonly termed as P and K solubilizing microorganisms. Owing to the abundant reserves of N-fixers and P&K-solubilizers of the earthworm intestinal tracts, the worm-excreted feed materials are far more enriched in nutrient value than any other types of composting processes [50]. The most encouraging fact regarding the benefit of vermicomposting is the cultivability of the microbial isolates obtained from earthworm guts or the vermibeds in-vitro and subsequent applicability on large scale basis for various beneficial activities like waste stabilization, soil quality rejuvenation, and crop production [60]. As such, previous researchers have detected strong immunity of vermi-isolated microorganisms against biotic and abiotic stresses [76]. A short account of vermicompost-associated resource full microbial species is presented in the Table 2.4.

Table 2.4: Plant growth promoting microorganisms identified from vermicompost and vermicompost amended soils

Microbe	Type	Isolation substrate	Resource recovery	Reference
Burkholderia spp.	Bacteria	Earthworm gut	P-solubilizer	[60]
Serratia marcescens	Bacteria	Earthworm gut and vermicompost	P & Zn-solubilizer, production of indole acetic acid, suppression of phytopathogenic fungi in soil	[60,80]
Kluyvera ascorbata	Bacteria	Earthworm gut	N-fixer and P-solubilizer	[60]
Species of Bacillus, Pseudomonas, Rhizobium, and Azotobacter	Bacteria	Vermicompost	Production of indole acetic acid, siderophore, ammonia, HCN, and catalase	[81]
Pseudomonas stutzeri and P. mosselii	Bacteria	Vermicompost amended soil	P-solubilization and production of indole acetic acid, siderophore, etc.	[82]
Enterobacter spp., Aeromonas spp., and Bacillus spp.	Bacteria	Earthworm gut and vermicompost	Production of indole acetic acid	[83]
Emericella nidulans	Fungus	Vermicompost	P-solubilizer	[84]
Streptomyces spp	Actinomycetes	Vermicompost and vermicompost amended soil	Production of indole acetic acid, siderophore, ammonia, HCN, and extracellular enzymes	[85]
Lysinibacillus fusiformis, B. safensis, Pseudomonas resinovorans, and Sphingobacterium daejeonense	Bacteria	Vermiwash	Biocontrol agents against root nod nematode	[86]
Bacillus megaterium and Lysinibacillus spp	Bacteria	Worm coelomic fluid	Biocontrol agents against root nod nematode	[86]
Bacillus subtilis, B. icheniformis, B.paranthracis, and B. toyonensis	Bacteria	Earthworm gut	Production of indole acetic acid, siderophore, ammonia, and extracellular enzymes	[87]

Although papers related to microbial resource recovery from vermicompost, earthworm, and vermicompost-aided media are limited in the literature, there is a sign of increase of similar publications in recent past (Table 2.4). As such, the vast microbial diversity of the vermicompost based systems can be treated as resource recovery if the task of isolation is meaningfully executed. For example, while targeting the fly ash-vermicompost as a domain for isolation of P-solubilizing microorganism we ended up in isolating a potent fungal strain of *E. nidulans* that not only demonstrated significant P-solubilization potential *in-vitro*, but also considerably improved crop growth when applied *in-vivo* field experiment [84]. Rostami et al. (2021) [87] recently isolated eleven bacterial species from earthworm gut and animal waste vermicompost-wash that showed high lethal effect on root nod nematode pathogen. Apart from bacteria, actinomycetes species with multiple plant growth promoting traits could be isolated from herb-waste vermicompost and its aided-soil [85]. Similarly, Andleeb et al. (2022) [87] could isolate several bacterial strains from earthworm gut that exhibited traits like indole acetic acid production, siderophore production, production of extracellular enzymes, etc. Hence, we postulate that in waste-based vermicomposting systems not only convert toxic and complex solid waste into valuable organic manure but also can offer unlimited microbial resources for achieving the sustainable development goals of the world.

2.4 Vermicompost and soil organic C pool – addressing critical questions

The health and sustainability of agricultural soils largely depends on the soil organic carbon (SOC) reserves. The decline in SOC levels has been a major concern in agriculture, and there is a growing interest in developing sustainable approaches to increase SOC levels. One such approach that has captured remarkable consideration recently is vermitechnology. Vermicomposting is the mechanism of composting bio-based litter utilizing earthworms. Vermicomposting is the mechanism of composting bio-based litter utilizing earthworms. This process produces a nutrient-rich product called vermicompost, which is known to ameliorate soil health and fertility. However, there are critical questions that need to be talked about concerning the role of vermicompost in increasing SOC levels. This chapter aims to address some of these critical questions. Vermicompost has been shown to impart an elevator-like effect on SOC reserve in several studies [50]. In a study conducted in India, the application of vermicompost increased SOC levels by 34% compared to chemical fertilizer [88]. Similarly, a study performed in

China, coins that the application of vermicompost increased SOC levels by 22% compared to control [89]. Overall, these studies imply that vermicompost has the probable constituents that helps in increasing the SOC levels in intensively cultivates soils.

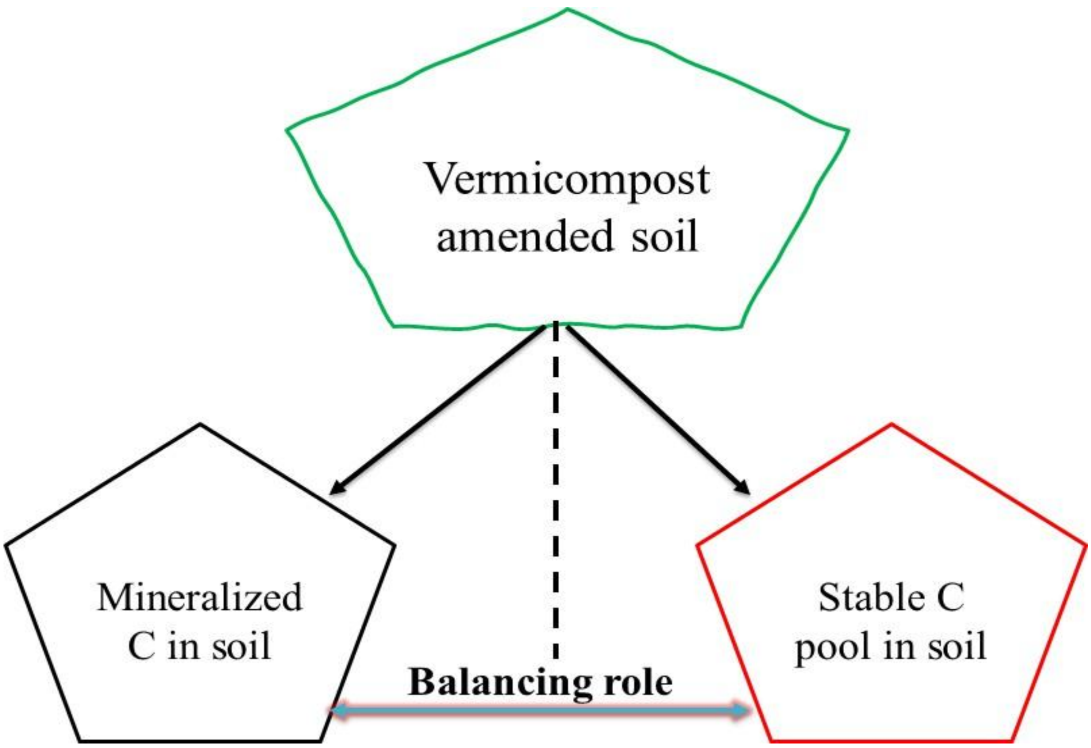

Fig. 2.3: The balancing impact of vermicompost amendment on soil carbon pool

Several factors can affect the contribution of vermicompost to the SOC pool. One such factor is the quality of the vermicompost that considerably depends on the earthworm species, nature of feedstock, and the vermicomposting process [90]. As such, the quality indicators of a good vermicompost are C/N ratio, humification status, microbial biomass gain, and nutrient status [91]. Therefore, the vermicompost quality is a vital factor in determining its contribution to the SOC pool. Another factor that can affect the contribution of vermicompost to the SOC pool is the rate and frequency of application. In a study conducted in China, vermicompost at a rate of 20 t/ha increased SOC levels by 22% compared to control, while the application of vermicompost application at a rate of 10 t/ha had no significant effect on SOC levels [89]. In contrast, a study conducted in India revealed the application of vermicompost at a frequency of once every two years significantly enhanced SOC levels, while the vermicompost addition at a frequency of once every three years had no significant effect on SOC levels [88]. These studies suggest that the rate and frequency of application of vermicompost are important factors in determining its contribution to the SOC pool. Hence, we postulate that the quality of vermicompost and the rate and frequency of application are important factors that need to be considered to maximize its contribution to the SOC pool. Further research is needed to address these critical questions and develop guidelines for the effective use of vermicompost in increasing SOC levels in soil.

2.4.1 Soil organic storage – Can vermicompost help?

Soil organic carbon (SOC) storage in soils plays a determining role in sustaining soil health, water retention, and physical composition of soils. However, SOC depletion is a growing concern worldwide because of the changes in land-use patterns, agricultural practices, and resilience to climate change. To address such issues, studies have explored various methods to enhance SOC storage in soils. One such method is vermicomposting, which involves the fortification of diverse solid wastes into an effective organic manure. Vermicompost is known to have several benefits, including improved soil health, increased crop yield, and reduced greenhouse gas emissions. However, its potential to enhance SOC storage in soils is still unclear.

Studies have shown that vermicompost application can increase SOC content in soils. Zhou et al. (2019) [89] demonstrated significant increase in SOC content of vermicompost-aided soil in a greenhouse-based trial with vegetables. The study found that after two years of vermicompost application, SOC content increased by 0.77% in the topsoil (0-20 cm) from that of the control. Similarly, Khwairakpam et al. (2015) [92] observed that vermicompost incorporation significantly increased SOC content in a vegetable field. The study reported that after three years of vermicompost application, SOC content increased by 41% in the topsoil (0-15 cm). Such increased SOC stock in soils after vermicompost application can be attributed to several factors. First, vermicompost contains substantial amount of organic matter thereby providing a steady source of food for the soil microbes that eventually decompose organic matter and release nutrients, including carbon, back into the soil [93]. Second, vermicompost has a high microbial diversity, which enhances soil biodiversity and promotes nutrient cycling [94]. Third, vermicompost contains humic substances, which are stable organic compounds that can persist in soils for decades, contributing to long-term SOC storage. Despite the potential benefits of vermicompost application in enhancing SOC storage in soils, some critical questions need to be addressed. For instance, the optimal vermicompost application rate and frequency to achieve maximum SOC storage are still unknown. Moreover, the effect of vermicompost application on SOC stability and turnover rates needs to be investigated. Vermicompost has the potential to enhance SOC storage in soils, thereby contributing to climate change mitigation and soil health improvement. However, more field-based studies backed by in-depth mechanistic lab-based experiments are essential to determine the optimal application rate, application frequency, and the long-term impacts of vermicompost use on the storage of SOC in agricultural soils.

2.4.2. How soil microbial community responds to vermicompost application?

Soil microbial reserves are essential for nutrient cycling, soil health, and plant growth [95]. Vermicompost, a rich source of beneficial microorganisms, has been demonstrated to augment the diversity and activity of the soil microbial pool to large extent [50]. Microorganisms involved in the cycling processes of the N, P, K, and S are vital to maintaining soil fertility [96]. Therefore, understanding how vermicompost mobilizes the soil microbial communities is essential.

In general, vermicompost application has been shown to encourage the microbial community diversity and their functional roles in soil-plant interfaces [97,98]. Additionally, vermicompost has been found to increase the activity of soil enzymes that are responsible for maintaining the nutrient-cycling processes on the earth surface [58,97]. The application of vermicompost has also been shown to promote the growth of beneficial microorganisms like mycorrhizal fungi [97]. While the short-term effects of vermicompost on soil microbial communities are well documented, the long-term effects are less clear. A few studies have observed a decline in microbial activity and diversity following long-term vermicompost incorporation in cropped soils [99,100]. However, other studies have found no significant changes in microbial diversity or abundance [98]. As such, the long-term effects of vermicompost on soil microbial communities are likely to be influenced by factors such as vermicompost quality, application rate, and soil type [97]. Nevertheless, the short-term benefits of vermicompost addition regarding microbial rejuvenation in soil cannot be overemphasized as evidenced from different field-based studies [48,101]. However, the long-term (i.e., five year long or ten year long) effects on soil microbial reserves are yet to be well understood due to lack of research evidence on vermicompost amendments in the literature, and hence further research in this area is essential.

Nonetheless, vermicompost remains a valuable tool for refining soil health, nutrient cycling, and crop production.

2.4.3. Effects on soil biochemical health (enzymes and hormones)

Soil health is a critical aspect of agronomy, and it has become increasingly important to upgrade the fertility of soil and quality to ensure sustainable agriculture. Vermicompost, a product of vermicomposting, happens to be an excellent soil amendment that provides various benefits to soil health. Vermicompost use has been shown to significantly impact soil biochemical health, including the activities of soil enzymes and hormones. In this chapter, we will discuss the application of vermicompost and its effects on soil biochemical health, focusing on enzymes and hormones, and provide insights into how its application can upgrade the health of the soil.

Soil enzymes are critical components of soil biochemical health, and their activity is an indicator of soil fertility and nutrient cycling. Vermicompost application has been shown to significantly increase the activity of certain enzymes in the soil, like protease, phosphatase, urease and cellulase [102,103]. Urease is an enzyme responsible for the catalysis of urea to hydrolyze into ammonia and carbon dioxide, and its activity is essential for the availability of nitrogen in the soil. Proteases and phosphatases are enzymes that are involved in the breakdown of proteins and phosphorus, respectively, and are essential for nutrient cycling in soil. The cellulose enzyme is responsible for the breaking down of cellulose, an essential component of plant cell walls, into glucose, and its activity is critical for carbon cycling in soil.

Soil hormones are signaling molecules responsible for the regulation of different physiological responses in plants and microorganisms. Soil application of vermicompost has shown to increase the concentrations of several hormones, like cytokinins, gibberellins and auxins [24,103]. Auxins are hormones that regulate growth in plants and their development, and the increased concentration of them in the soil can induce growth in plants. Cytokinins are hormones that promote cell division and delay senescence, and their increased concentration in the soil can improve plant productivity. Gibberellins are hormones that regulate plant height and seed germination, and their increased concentration in the soil can promote plant growth.

Vermicompost application has significant effects on soil biochemical health, including the activities of soil enzymes and hormones. Vermicompost has been found to increase the activity of several critical soil enzymes, including urease, protease, phosphatase, and cellulase, which are essential for nutrient cycling in soil fostering the productivity and growth of plants. Overall, the application of vermicompost can be an effective soil alteration for improving soil biochemical health and promoting sustainable agriculture.

2.4.4 How vermi-technology enhances sustainable agricultural growth?

Vermi-technology, which involves the use of earthworms to decompose organic waste into nutrient-rich vermicompost, has shown significant potential for enhancing productive and sustainable agricultural growth [104]. When combined with plant growth-promoting rhizobacteria (PGPR), this technology can further augment soil fertility and plant health [105]. Vermicompost provides a hospitable environment for PGPR, enhancing their effectiveness in the rhizosphere. These bacteria enhance nutrient uptake, promote root growth, and improve plant resilience against diseases and environmental stresses, resulting in healthier and more productive crops [106]. The integration of vermi-technology with PGPR presents a sustainable approach to agriculture by reducing the dependency on chemical fertilizers and pesticides. Vermicompost enriches the soil with organic matter and essential nutrients, while PGPR enhances nutrient bioavailability and protects plants from pathogens [105]. This synergistic effect not only boosts crop yields but also contributes to soil health and biodiversity, creating a more sustainable agricultural system. By adopting these bio-fertilization techniques, farmers can achieve long-term productivity and environmental sustainability, paving the way for resilient agricultural practices. The activities of plant growth-promoting rhizobacteria (PGPR) are significantly enhanced by the presence of earthworms in vermicomposting systems. Earthworms play a crucial role in the decomposition of organic matter, leading to the production of nutrient-rich vermicompost [107]. This process creates an optimal environment for PGPR to thrive and perform their beneficial functions. Earthworms facilitate the breakdown of organic matter through their digestive processes, which not only reduces the particle size of the organic material but also increases the surface area for microbial colonization. The earthworms' gut and castings are rich in microorganisms, including beneficial bacteria, which are released into the vermicompost. This microbial diversity and abundance in vermicompost provide a conducive environment for PGPR to proliferate [108]. Additionally, the constant movement of earthworms through the soil helps distribute these beneficial bacteria more evenly, enhancing their interaction with plant roots.

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