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Vermicomposting with microbial amendment: implications for bioremediation of industrial and agricultural waste

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Abstract

Improved agricultural practices and rapid industrialization have led to huge waste generation, and the management of this waste is becoming a global concern. The process of vermicomposting has emerged as a method of choice for converting waste into useful manure, with evidence of increase in crop productivity. During vermicomposting, the collective activities of decomposing microorganisms and earthworms lead to the humification of organic/inorganic waste, thereby generating the final product called vermicompost. Different types of industrial wastes such as waste from paper industries, tanneries, sugar mills, and pulp and textile industries have been effectively converted to vermicompost and successfully used to improve plant growth. The vermicompost thus formed was also demonstrated to increase the production of pharmaceutically important plant secondary metabolites such as withanolides and polyunsaturated fatty acids. Microbial amendment with different bacterial and fungal strains during vermicomposting further proves to be beneficial by increasing nitrogen content, decomposing organic waste, providing aeration, and stabilizing the vermicompost. These microorganisms after passing through the earthworm's intestine increase in numbers in the vermicast, thus becoming enriched in vermicompost, which is particularly important for their use as biofertilizers. The precise role of different microbial pretreatments in improving the quality of vermicompost generated from industrial and agricultural waste is, however, not completely understood. To fill this gap in knowledge, the present article aims to review published literature to highlight the potential of microbial amendment during vermicomposting for bioremediation of industrial and agricultural waste. Microbial pre-composting followed by vermicomposting emerges as an eco-friendly and economical approach for managing agricultural and industrial waste.

Key words: vermicompost, agricultural and industrial waste, fungal amendment, phosphate-solubilizing bacteria, nitrogen-fixing bacteria, organic manure

Introduction

Agricultural waste is the most wasted form of energy and is widely available in developing countries where around 70% of the rural population primarily depends on agriculture (Jimenez-Lopez et al., 2020). Except for their utilization as fodder for cattle, more than half of the paddy straw and cane trash is simply burned, which further aggravates the pollution issue. India is the second largest paddy producer with the annual production of 117.47 million tons. This, however, results in the production of paddy straw of around 150 million tons, where only half is used as fodder, and the rest is burned due to time constraints of farmers (Sain, 2020). Around 70 million tons of cane trash is also produced in India, which because of the high content of silica has no commercial use and is entirely burned (Ranjan et al., 2020). Other

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crops such as cotton, maize, millets, sunflower, groundnut, coconut, and pulses also contribute to the generation of large amounts of agro-waste (Devi et al., 2017). Furthermore, to meet the food demand in highly populated countries like India, farmers are highly dependent on the use of nitrogen, phosphorus, and potassium fertilizers to increase food production per hectare. India is only next to China in terms of fertilizer consumption (Randive et al., 2021). Although internationally the estimates of agricultural waste generated are rarely reported, significant proportions of the total waste in developed countries are still contributed by agricultural wastes (Maji et al., 2020). This issue is likely to intensify if farming systems continuously evolve in developed countries. Approximately billion tons of agricultural waste are produced annually, of which 80% is contributed by organic waste (Maji et al., 2020).

A huge amount of solid, liquid, and gaseous waste is produced by almost each industry, which causes environmental problems because of inefficient management and recycling techniques. The conventional disposal methods of this waste include land filling, burning in open air, or dumping in open land, which by leaching or conversion to toxic chemicals cause air and soil pollution (Saxena et al., 2020). Therefore, the key agenda of municipalities and scientists worldwide is to facilitate proper disposal and management of these wastes. The organic industrial waste with nontoxic and biodegradable properties can be used as raw materials for vermicomposting. Past research has also demonstrated the testing of various types of industrial wastes/sludges for their potential for conversion into vermicompost (Yadav and Garg, 2011; Amouei et al., 2017; Karmegam et al., 2021).

It remains debatable whether vermicomposting is efficient in reducing the number of human pathogens in industrial and agricultural waste. Vermicomposting is a mesophilic process where the temperatures are generally kept below 35 °C to prevent the worms from dying. However, according to the standards of Environmental Protection Agency (EPA), the compost should be exposed to high temperature (55–70 °C) for at least 72 h (Edwards et al., 2010). Previous studies have demonstrated that the passage of solid waste through the intestine of worms reduces the number of pathogens such as *Salmonella* and fecal coliforms in cow and pig manure vermicomposts (Monroy et al., 2009; Karimi et al., 2017). The studies also highlighted the necessity of evaluating the number of pathogens prior to using vermicompost in soil for preventing disease transmission (Monroy et al., 2009; Karimi et al., 2017).

The process of vermicomposting involves a collective action of microorganisms and earthworms to convert waste into useful manure. Vermicomposting has been effectively used to detoxify industrial wastes, converting them to a manure rich in humic substances and promoting plant growth (Bhat et al., 2018). The strong metabolic system of earthworms, their gut microbial load, and their chloragogen cells provide them the ability to detoxify heavy metals and volarize industrial waste (Bhat et al., 2018). Recycling organic waste through vermicomposting is being considered as an ecofriendly solution. Earthworms act as a natural bioreactor and proliferate along with other microorganisms, thus providing the required conditions for the biodegradation of solid waste. Although microorganisms are responsible for the decomposition of organic waste, earthworms are the drivers for this process by conditioning the substrate and altering its biological activity. The final vermicompost contains different compounds such as nitrogen, phosphorus, potassium (NPK), organic carbon, micronutrients, and microflora (Iqbal et al., 2015). These compounds are responsible for the establishment of enriched soil with high porosity and water holding capacity that contain nutrient in the form readily taken up by the plants. The success of the process depends upon several parameters such as raw material used, pH, temperature, moisture, aeration, and earthworm species. Numerous microorganisms such as bacteria, fungi, and actinomycetes have been associated with the composting process (Palaniveloo et al., 2020). It is clear that a microbial community is required for the decomposition of organic matter (Wang et al., 2021).

Microorganisms such as bacteria, actinomycetes, and fungi are the most important microorganisms that play an important role during vermicomposting (Liu et al., 2021). The microbial populations of earthworm's gut and cast produces an extensive variety of natural materials such as polysaccharides, including cellulose, sugar, lignin, chitin, starch, and polylactic acid, thereby accelerating the process of composting (Aira et al., 2007). A wide range of stomach-related enzymes such as amylase, cellulase, chitinase, protease, lipase, and urease are present in earthworms and the microorganisms because of decomposition of organic matter (Munnoli et al., 2010).

At various stages of vermicomposting, the majorly enriched taxonomic groups of bacteria include Bacteroidetes, Chloroflexi, Proteobacteria, Firmicutes, and Actinobacteria (which constitute almost 83–93% of total bacteria) (Wang et al., 2017; Zhang et al., 2016). These bacterial species are generally known for degrading recalcitrant organic compounds such as lignocelluloses (DeAngelis et al., 2011). The genera Bacteroidetes can effectively degrade macromolecules including chitin and cellulose (Manz et al., 1996), while Firmicutes have been found to metabolize cellulose, lignin, lipids, proteins amino acids, and sugars as they produce enzymes such as proteases, cellulases, lipases, and other extracellular enzymes (Lim et al., 2014). Peroxidases such as lignin peroxidase-type enzymes are produced by Actinomycetes to effectively degrade lignin (Varma et al., 2017). The most abundant and widely distributed fungal phylum during the aerobic composting process is Ascomycota as they can grow rapidly under the conditions of high C : N ratio (Langarica Fuentes et al., 2014). The other dominant fungal phylum includes Basidiomycota as it can perform oxidative biotransformation by secreting lignin-degrading enzymes (Schmidt-Dannert, 2016).

Microbial pretreatment with selective microorganisms was also found to be useful for reducing the degradation time by earthworms and for producing enriched vermicompost. Previous studies have shown that combining vermicomposting with pre-composting of the raw material accelerates the process of composting and reduces the composting time (Nedgwa and Thompson, 2001; Pérez-Godínez et al, 2017). Since the pre-decomposed waste is favored by earthworms, pre-decomposition with some efficient microorganisms is desirable (Rini et al, 2020). Therefore, this article aimed to review published literature to highlight the potential of vermicomposting with microbial amendment for bioremediation of industrial and agricultural waste.

Process of vermicomposting

Aristotle said around 2,350 years ago that "Earthworms are intestines of the earth," which was found to be correct and verified only in the twentieth century. Darwin also stated that "No other creature has contributed to the building of earth as earthworm." The science of raising and breeding earthworms is called "Vermiculture," which is generally performed to harvest the potential of earthworms for waste reduction and fertilizer production (Sinha et al., 2010). The process of vermicomposting involves the production of an organic fertilizer, also known as vermicompost, by biodegradation of organic waste with the help of earthworms to avoid waste disposal and to produce high-quality compost. Being considered as top "soil scientists," earthworms can convert common soil by breaking down the organic matter contained in it to a superior quality fertilizer that is mainly composed of their valuable castings. Aerobic conditions are maintained by earthworms during this process, which accelerate the biological decomposition of organic matter. This process also results in an excessive increase in the number of earthworms. These earthworms can be used for animal protein supplementation and as a fish bait, but they are always considered as a byproduct of the vermicomposting process, while their castings that enrich vermicompost always remains the principal product (Wang et al., 2007).

Vermicomposting of industrial waste

Researchers are attempting to characterize and use different methods for producing enriched vermicompost from industrial waste. Several studies have highlighted the potential of the vermicomposting process to detoxify industrial waste and to convert it into useful fertilizers. A recent study highlighted the conversion of coir industrial waste to enriched vermicompost (Karmegam et al., 2021). In another study, to analyze the periodic changes during vermicomposting of sludge from bakery industry, different proportions of the sludge ranging from 10 to 50% were mixed with cow dung followed by evaluation of their physicochemical parameters at intervals of 21 days. It was found that earthworms progressively increase the NPK content with a simultaneous decrease in total organic carbon content. The C : N ratio was significantly reduced (65.4–83.5%) in all blends as compared to that in the initial blends (Yadav and Garg, 2019). Tannery waste that includes hydrolyzed animal flesh in solid state was also found to be useful after conversion to vermicompost. This waste when mixed in different proportions with animal manure followed by vermicomposting by earthworms was found to increase plant height (10%), stem girth (8.9%), and leaf numbers (14%) of tomatoes (Ravindran et al., 2019).

Vermicompost produced from paper sludge was found to increase ginseng root yield by 40 t/ha as compared to untreated soil. The application of this vermicompost elevated the pH of the fields, which is effectively required for shifting the cultivation from rice to ginseng. However, the cultivation of ginseng in vermicompost-treated soil had no effect on increasing the concentration of ginsenosides in plant roots (Eo and Park, 2019). Grape marc, a waste product of wine-making industry can also be processed by vermicomposting as an effective approach for returning nutrients to the soil. A continuous feeding system has been demonstrated for vermicomposting grape marc for 12 months in outdoor conditions. The microbial biomass, dissolved organic carbon, and $N{-}NH_4^+/N{-}NO_3^-$ contents were enriched in the top layers of this feeding system after 12 months, thus imparting it good fertilizing properties (Částková and Hanč, 2019).

The vermicomposting of wastes from palm oil mill has also been recognized as an ecofriendly and efficient method for converting it into a valuable product. The mixture of an acidic effluent from palm oil mill and palm pressed fiber when vermicomposted for 45 days using *Lumbricus rubellus* was found to significantly increase the concentration of NPK with a simultaneous decrease in the C : N ratio. This vermicompost was also found to improve the seed germination of mung bean (Rupani et al., 2017). The solid household waste and even the sludge from the wastewater treatment plant can be converted into a high-quality compost by vermicomposting (Amouei et al., 2017).

Thus, these studies highlight that earthworms are very helpful in recycling industrial waste and transforming it into valuable products. If optimum conditions are provided and an adequate amount of earthworms is added to industrial waste, a high-quality vermicompost, as compared to the traditional compost, can be produced, which can serve as a good source of plant nutrients and as a soil conditioner for crops. However, most of these studies are conducted on a laboratory scale, which highlights an urgent need for pilot- or field-scale studies for commercial exploitation of vermicomposting of industrial waste.

Vermicomposting of agricultural waste

Agricultural lignocellulosic waste can be successfully vermicomposted to produce a good-quality manure (Fig. 1). This lignocellulosic waste when mixed in diffe-

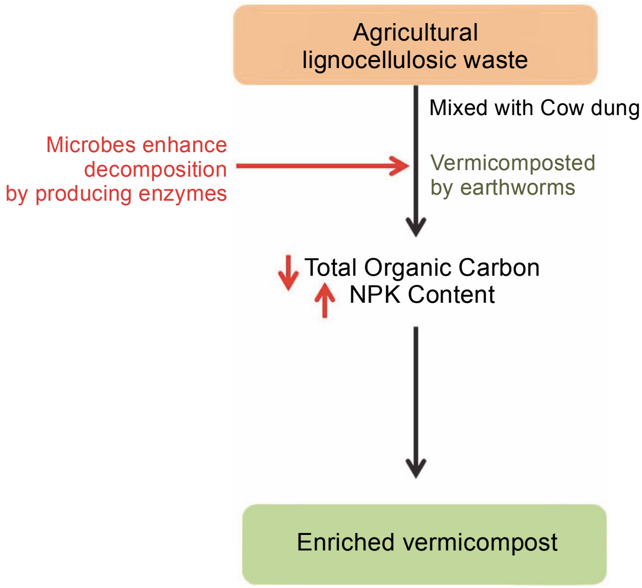

Fig. 1. General scheme of vermicomposting and microbial decomposition of agricultural waste

rent proportions with cattle manure and vermicomposted by adding *Eisenia fetida* earthworms showed decreased total organic carbon (268–320 g/kg) and increased NPK content in the waste after 105 days of vermicomposting. It also increased the heavy metal content with their benefit ratio ranging between 0.06 and 5.1 (Sharma and Garg, 2019). In another study, a mixture of wheat straw and rice straw (2 : 1 ratio) with cow dung or fern *Azolla pinnata* or fungus *Aspergillus terreus* was composted aerobically followed by vermicomposting. The analysis of their surface-structural-morphological features by SEM showed decreased particle size, increased porosity, and compaction with the progress in vermicomposting. Furthermore, mixtures that contained agricultural waste, cow dung, azolla, and fungus showed enhanced degradation as compared to other mixtures (Arora and Kaur, 2019). The vermicomposting of banana stem waste and cow dung mixture for 60 days showed increased content of plant nutrients (Fe, P, K, Ca, and Mg levels) (Khatua et al., 2018). Fly ash was also ameliorated by vermicomposting after mixing with cattle dung (Sohal et al., 2021).

Water hyacinth (*Eichhornia crassipes*), an important heavy metal phytoremediation plant, has been demonstrated to be a source of organic matter for earthworms, and the vermicomposting of water hyacinth was found to lower the toxic metal arsenic content to 23.9 ± 1.55 mg/kg in mature compost as compared to that in control soil (134.69 ± 2.47 mg/kg arsenic) (Majumdar et al., 2018). Vermicomposting is also envisaged as a management system for the wild shrub Scotch broom (*Cytisus scoparius*), which is widely distributed worldwide and creates threat for the growth of other plant species by releasing high content of polyphenols. Vermicomposting for 42 days by using *Eisenia andrei* earthworms was found to reduce the content of volatile solids in plant waste, substantially reduce its biomass by 84%, and eliminate its polyphenol-associated phytotoxicity (Domínguez et al., 2018). Sea weeds such as *Gracilaria corticata, Sargassum swartzii, Sargassum wightii,* and *Halimeda gracilis* when first naturally decomposed and mixed 1 : 1 with cow dung, followed by vermicomposting by adding *Perionyx excavatus* worms, were found to produce an enriched vermicompost. Composting this mixture for 60 days resulted in decreased organic carbon (−37.78 to −50.97%) and increased NPK content (26.72–78.17%) in the final product. The vermicomposting of seaweed and cow dung combination resulted in enrichment in the total microbial population and showed increased growth/reproduction of the earthworm *Perionyx excavatus* as compared to that in cow dung alone (Ananthavalli et al., 2019).

A high content of lignin is found in garden wastes, which hinders the growth of both microorganisms and earthworms during vermicomposting. However, the mixing of spent mushroom substrate and cattle manure with garden waste was found to promote the growth of earthworms and improve the quality of vermicompost by increasing the biomass and survival rate (both cocoon and juvenile) of earthworms (Gong et al., 2019). The mixture facilitates organic matter, lignin, and cellulose decomposition by significantly increasing the activities of urease, cellulase, dehydrogenase, and alkaline phosphatase as compared to that in control and also accelerates nitrification and increases NPK concentration in the final vermicompost. The mixture of garden waste, spent mushroom substrate, and cattle manure in 2 : 1 : 1 ratio showed the highest organic matter decomposition, high growth rate of *E. fetida*, and the highest germination index of tomato seeds and Chinese cabbage (Gong et al., 2019).

Soil amendment by vermicomposting has also been evaluated to increase the production of useful molecules. Application of vermicompost was found to improve the content of polyunsaturated fatty acids (PUFA: ω-3/ω-6 fatty acids) by approximately 35% in linseed seeds and thus also played an important role in Integrated Nutrient Management (Makkar et al., 2019). Soil microbial communities were also found to be activated by applying a combination of vermicompost (3.5 t/ha) and poultry manure (2.5 t/ha) and thus may prove to be useful for increasing plant production (Manjunath et al., 2018). The application of vermicompost to *Withania somnifera* (Ashwagandha) during its sowing and growing phases was found to increase the content of anticancer compounds called withanolides (Kaur et al., 2018). The amendment with vermicompost thus proves as an effective approach to improve the production of pharmaceutically important phytomolecules (Kaur et al., 2018).

Microbial amendment of vermicompost

Amendment with decomposers

Microorganisms provide a nutrient-rich source for growing earthworms, where fungi act as a major source and bacteria act as a minor source for nutrients (Edwards et al., 2004). Fungi are natural decomposers and obtain nutrients from dead plant matter. Digestion of the filamentous fungi by earthworms and their passage in the intestine further increases the number of fungi in the vermicast (Kristufek et al., 1992).

Soil fungi are considered to be an important food source for earthworms. Several fungal species (*Cladosporium cladosporioides, Rhizoctonia solani, Mucor* sp.*, Trichoderma viride, Fusarium nivale, Phlebia radiate, Aspergillus niger,* and *Coriolus versicolor*) have been reported for the pretreatment of organic waste before vermicomposting (Fig. 2). Organic wastes that are dry and acidic and possess low nitrogen are also degraded by fungi. Fungi also degrade complex polymers such as polyaromatic compounds or plastics (Kastner and Mahro, 1996). They prefer temperature ranging from 21 to 24°C. Fungi provide the aeration and drainage by stabilizing the compost into smaller aggregates. Though earthworms consume fungi within the organic matter to fulfill their nitrogen content, the viable count of different fungal species in earthworm castings was generally higher than that of the initial substrate during vermicomposting (Edwards and Bohlem, 1996). Most fungi tolerate high concentrations of polluting chemicals, as they have a complex enzymatic system and are able to degrade polymers and xenobiotics such as pesticides

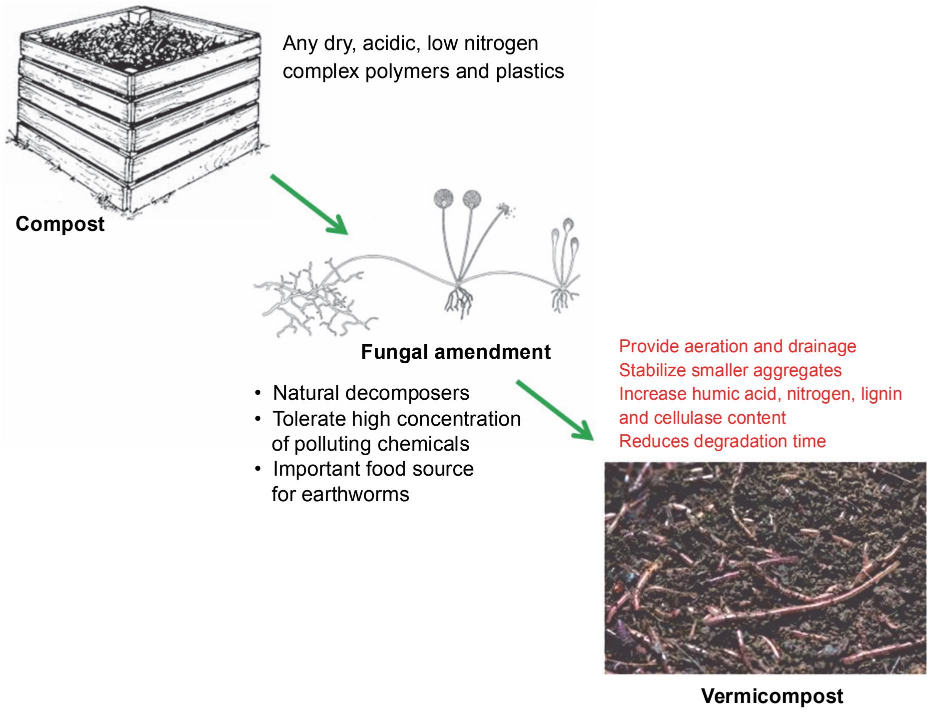

Fig. 2. Fungal amendment of vermicompost

(van der Gast et al., 2011); thus, they are important role players in bioremediation.

The addition of a biosurfactant rhamnolipid; *Phanerochete chrysosporium*, a cellulolytic and lignolytic fungus; and *Azotobacter chrococcum*, a free-living nitrogen-fixing bacterium to green waste was found to significantly increase the densities of both bacteria and fungi, activities of cellulase and urease, and growth rate of *E. fetida* earthworms during vermicomposting (Gong et al., 2017). Amendment with rhamnolipid and microorganisms improved the content of humic acid, nutrients, lignin, and cellulose in the final vermicompost (Gong et al., 2017). Agave bagasse, waste of *Agave tequilana* Weber generated during the production of tequila and fructans, is traditionally composted by a long process that requires 6–8 months (Moran-Salazar et al., 2016). The pre-composting of this waste by *Bjerkandera adusta* and other native fungi followed by vermicomposting (for 45 days) was found to enhance lignocellulose degradation and improve its physicochemical parameters. The pre-composting process led to the elimination of 90% of residual sugars from the bagasse in 30 days and effectively reduced its degradation time to 3 months (Moran-Salazar et al., 2016). Inoculation of two strains of the fungi *Trichoderma atroviride*, namely cellulase/xylanase-producing GVF10 and ligninase/celluloxylanase-producing RVF3, were found to increase the content of humic acid by more than 62% during vermicomposting of rice straw. The addition of these fungal species also reduced the vermicomposting time to 90 days (Maji et al., 2015).

The combination of vermicompost and arbuscular mycorrhizal fungi was also found to be effective in increasing the production of secondary metabolites in plants. A study by Silva and Silva (2020) demonstrated that the combination of *Acaulospora longula* and 7.5% vermicompost increased the phenol concentration in the leaves of *Punica granatum* plants. The increase of 116.11% in phenol concentration in the leaves of *P. granatum* was observed after 120 days of inoculation of this combination (vermicompost and arbuscular mycorrhizal fungi) as compared to that in the non-inoculated control (Silva and Silva, 2020).

Amendment with plant growth-promoting bacteria

Different bacterial biomasses also play an important role during decomposition of various organic substrates present in agricultural waste (Yasir et al., 2009). Glaser et al. (2004) revealed that the concentration of muramic acid could be used as an indicator for determining different bacterial biomasses. Previous reports have also

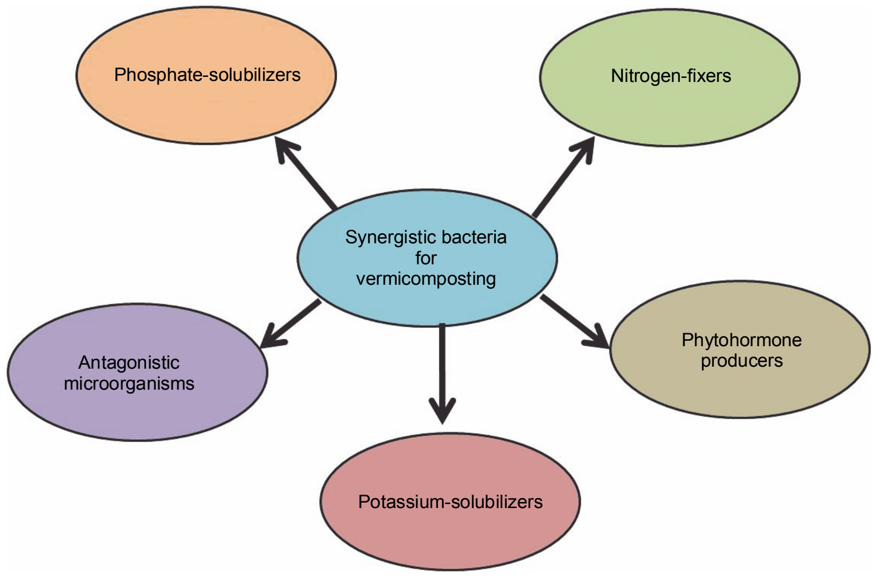

Fig. 3. Synergistic bacteria for vermicomposting. The addition of nitrogen-fixing, potassium-solubilizing, phosphate-solubilizing, and phytohormone-producing bacteria in organic waste synergizes with earthworms for the production of enriched vermicompost

indicated that the presence of indole acetic acid (IAA)-producing bacteria in vermicomposts promoted plant growth (Gopalkrishnan et al., 2014). Microbial amendment with two biofertilizer bacterial species, namely *Rhizobium leguminosarum* and *Azospirillum brasilense*, on the 30th day of vermicomposting was found to maintain sufficient viable population of these bacteria in the enriched vermicompost (Rajasekar et al., 2012). The phosphate-solubilizing bacterial species *Pseudomonas fluorescens* has been demonstrated to optimize vermidegradation and improve nutrient mineralization during vermicomposting of fly ash-cow dung-paper waste. This bacterial species was found to decrease the C/N ratio from 18 (without bacterial amendment) to 11 (with bacterial amendment) and improve phosphate availability by 48.3% (Lukashe et al., 2019). In another study, the increased uptake of phosphorus by wheat (20–39%) and tomato plant (26–53%) was observed after enrichment of various phosphate-solubilizing bacteria in added vermicompost, and the enriched vermicompost was even found to favor the growth of these plants on calcareous soil with low phosphorus concentration (Parastesh et al., 2019). Furthermore, a decrease in soil pH by 0.4–0.6 units and an increase in soil respiration rate, available phosphorus, and activity of alkaline phosphatase and soil dehydrogenase were observed after using the enriched vermicompost as compared to that in control, thus highlighting that phosphate-solubilizing bacteria-enriched vermicompost proved to be a potential solution for vegetative growth on calcareous soil and helped in better management of phosphorus fertilization (Parastesh et al., 2019). The addition of plant growth-promoting microorganisms such as *Azospirillum brasilense* and *Azotobacter chroococcum* during vermicomposting was found to improve the growth of rice, leaf chlorophyll content, grain yield, and activity of nitrate reductase (Mahanta et al., 2012). The NPK content was also significantly improved in the post-harvest soil after applying enriched vermicompost (Mahanta et al., 2012). The bioinoculation of sugarcane industry waste such as press mud, bagasse, and trash with a mixture of *T. viridae*, *Pleurotus sajorcaju*, *Pseudomonas striata*, and *A. niger* for 30 days followed by 40 days of vermicomposting was found to accelerate the waste degradation process and reduce composting time to 20 days. The compost thus formed was enriched in nutrients, which could sustain a high yield of crop and minimize soil depletion (Kumar et al., 2010).

Plant growth-promoting microorganisms (PGPMs) could lead to a better plant growth and to a plant more tolerant to stress conditions. Amongst PGPMs, *Azospirillum* belongs to the genera that can fix atmospheric nitrogen (Kumar and Singh, 2001; Fukami et al., 2018) and mineralize nutrients from soil. Vermicompost with good physicochemical properties and fortified with all nutrients and plant growth-promoting bacteria are or-

Table 1. Studies pertaining to microbial amendment during vermicomposting

S. No.	Study	Result	Reference
1	Optimizing vermicomposting process by inoculating with phosphate--solubilizing bacteria (*P. fluorescens*)	Improved biological activity, vermi-degradation, and nutrient release	Lukashe et al., 2019
2	Vermicomposting of different mixtures of rice straw/wheat straw/cattle dung/*Azolla pinnata/Aspergillus terreus*	Mixtures including both microbial species showed smallest particle size and maximum homogeneity	Arora and Kaur, 2019
3	Enriched vermicompost production with phosphate-solubilizing bacteria to increase phosphorus availability in sequential cropping under calcareous soil conditions	Significant increase in shoot phosphorus content of tomato and wheat plants, increased soil dehydrogenase, alkaline phosphates, and available P	Parastesh et al., 2019
4	Improvement of nutrient content of vermicompost amended with *Halothiobacillus neapolitanus*, rock phosphate, and steel dust	Increase in P and Fe content of vermicompost with the addition of *Halothiobacillus neapolitanus*	Shiraz et al., 2019
5	Investigation of the effects of biosurfactant rhamnolipid, *Phanerochete chrysosporium* (fungus) and *Azotobacter chroococcum* (nitrogen-fixing bacterium) on vermicomposting of green waste	Improved C/N ratio, nutrient content, electrical conductivity, lignin and cellulose contents and humic acid content	Gong et al., 2017
6	Evaluation of the effect of vermicompost enriched with *Azospirillum brasilense* and *Pseudomonas fluorescens* on okra ((*Abelmoschus esculentus* (L.) moench)	Improved total chlorophyll, carotenoid, protein, amino acid, and glucose content and NR activity in okra	Baliah and Muthulakshmi, 2017
7	Evaluation of agave bagasse degradation by *Bjerkandera adusta* (fungus) pretreatment and vermicomposting	Reduced the bagasse vermicomposting time to 3 months	Moran-Salazar et al., 2016
8	Preparation of vermicompost of paddy straw, water hyacinth, and sawdust using *Eisenia fetida* and beneficial microorganisms, including cellulolytic *Trichoderma viride*, nitrogen-fixing *Azotobacter chroococcum*, phosphate-solubilizing *Bacillus polymyxa*, and potassium-solubilizing *Bacillus firmus*	Significant decrease in pH, cellulose content, organic carbon, and C/N ratio along with an increase in N, P, and K content and humic acid	Das et al., 2016
9	Investigation of the effects of fungal strain *Trichoderma atroviride* on vermicompost production	Qualitatively superior vermicompost production with high humic acid content	Maji et al., 2015

Table 1 continue

S. No.	Study	Result	Reference
10	Investigation of phosphate and nitrogen content in enriched vermicompost compared to the nonenriched one	Significant increase in nitrogen content and nitrogenase activity following the addition of *Azospirillum*, but no difference in phosphorus content in both the vermicomposts	Iyer Shanti et al., 2012
11	Production of vermicompost enriched with biofertilizer microbial species (*Rhizobium leguminosarum* and *Azospirillum brasilense)*	Inoculation on the 30th day of vermicomposting maintained sufficient viable microbial population for 5 months	Rajasekar et al., 2012
12	Evaluation of vermicompost prepared from rice straw enriched with *Azospirillum brasilense*, *Azotobacter chroococcum*, and *Pseudomonas fluorescens* on the growth and yield of rice	Significant improvement in plant growth, leaf chlorophyll content, grain yield, and available N, P, and K content of rice with the application of enriched vermicompost	Mahanta et al., 2012
13	Optimization of the inoculum level and time of inoculum addition for the enrichment of biogas slurry vermicompost with *Azotobacter chroococcum* and *Bacillus megaterium*	Standardization of inoculum level and time of inoculation of beneficial microorganisms to vermicompost	Karmegam and Rajasekar, 2012
14	Vermicomposting of food waste and its enrichment using nitrogen-fixing *Rhizobium* sp. and phosphate-solubilizing *Pseudomonas* sp. as biofertilizers	Improved germination and growth of *Vigna unguiculata* (L) Walp following the application of enriched vermicompost.	Pradeepa et al., 2011
16	Pretreatment of waste from sugar-cane industry, bagasse, press mud, and trash with *Pleurotus sajorcaju*, *Trichoderma viridae*, *Aspergillus niger*, and *Pseudomonas striatum* followed by its vermicomposting	Decrease in time required for vermicomposting and production of nutrient-enriched vermicompost	Kumar et al., 2010
16	Vermicomposting of textile mill waste and cow dung with nitrogen-fixing and phosphate-solubilizing bacteria *Azotobacter chroococcum*, *Azospirillum brasilense*, and *Pseudomonas maltophila*	Increased nitrogen content of vermicompost with *Azotobacter chroococcum* and increased phosphorus content with *Pseudomonas maltophila*	Kaushik et al., 2008
17	Preliminary studies on vermicomposting wheat straw after pretreatment with *Pleurotus sajorcaju*, *Trichoderma harzianum*, *Aspergillus niger*, and *Azotobacter chroococcum*	Significant decrease in cellulose, hemicellulose, and lignin content and increase in N, P, and K content of vermicompost pretreated with microbial inoculants	Singh and Sharma, 2002
18	Optimizing the vermicomposting process by inoculating with *Azotobacter chroococcum*, *Azospirillum lipoferum* (nitrogen-fixing strains) and *Pseudomonas striata* (phosphate-solubilizing bacteria)	Increased content of nitrogen and phosphate	Kumar and Singh, 2001

ganic amendments for enhancing soil fertility, promoting plant growth, and controlling pathogen infection for sustainable agriculture (Fig. 3, Table 1). The amendment of vermicompost with *Halothiobacillus neapolitanus* with subsequent addition of 5% sulfur mineral and phosphorus rock (10%) or steel dust (5%) showed a significant decrease in pH (4.6–5), an increase in phosphorus content (130%), and an increase in Fe concentration (45%) after incubation for 40 days. The improved content of phosphorus and iron in the vermicompost may be because of their increased solubilization by *H. neapolitanus* from phosphate rock or steel dust (Shiraz et al., 2019).

The application of vermicompost enriched with nitrogen-fixing bacteria *Azospirillum brasilense* to the okra (*Abelmoschus esculentus* (L.) Moench) plant was found to result in greater plant growth and also improved soil quality (Baliah and Muthulakshmi, 2017). The enriched vermicompost improved biochemical characteristics of the Okra plant, such as higher content of carotenoids, chlorophyll, glucose, and protein and also showed increased nitrate reductase activity (Baliah and Muthulakshmi, 2017). The addition of nitrogen-fixing bacteria *Azotobacter chroococcum* along with phosphate-solubilizing *Bacillus polymyxa*, potassium-solubilizing *Bacillus firmus*, and cellulolytic *Trichoderma viride* during the vermicomposting process of agricultural organic waste containing paddy straw, sawdust, and water hyacinth improved the growth performance, cocoon production, and biomass of earthworms (Das et al., 2016). A reduction in the overall time of composting was noted, along with enrichment in the NPK content of the product. Nitrogen-fixing *Rhizobium* and phosphate-solubilizing *Pseudomonas* were added in a 1 : 1 ratio to the vermicompost, and this mixture when applied to soil at the concentration of 50 g/10 kg soil improved the growth and germination of *Vigna unguiculata* (L) Walp (Pradeepa et al., 2011).

As there is no thermophilic stage during the process of vermicomposting, there are concerns for the presence of pathogens that may prove to be potential health hazard (Swati and Hait, 2018). In a previous study, the grape marc substrate was artificially inoculated with pathogenic microorganisms such as thermotolerant coliform bacteria (TCB), *Enterococcus* spp., *Escherichia coli*, and *Salmonella* spp., and the reduction in the number of these microorganisms in the grape marc substrate was monitored during vermicomposting. A significant decrease in the levels of defense molecules such as lipopolysaccharide-binding protein and fetidin/lysenins and a high reduction in pathogen numbers were observed in the grape marc substrate after adding earthworms as compared to the substrate without earthworms (Roubalova et al., 2019). High-throughput sequencing for the difference in microbiome between the intestines of earthworms and the grape marc substrate highlighted that the pathogens were eliminated during the passage of food from the earthworm's gut.

Conclusions and future perspectives

During vermicomposting, the interactions between detritivorous earthworms and microorganisms modify the biochemical and physical properties of the organic waste and accelerate the stabilization of organic matter. Microorganisms and earthworms interact at various levels to digest the organic waste and convert it to useful manure, and the produced manure depending on the microbial inoculum used exhibit different properties and beneficial effects on plant growth. However, the vermicomposting of organic wastes may lead to leftover toxicities, for example, of heavy metals that may exert adverse effects on plant growth. Therefore, bioassays are needed to estimate the toxicity level of the generated vermicompost for its safe application to crop fields. Understanding the mechanisms of microbial transformations that occur during vermicomposting of organic matter can also help in developing strategies for efficient disposal of organic wastes.

Conflict of interest statement

The authors declare no conflict of interest.

Data availability statement

Data sharing not applicable to this article as no datasets were generated or analyzed during the current study.

Author contributions

P. Vyas and J. Gupta reviewed the literature and wrote manuscript. S. Sharma revised and formatted the manuscript. All authors approved the version to be published.

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