



Review Vermicomposting—Facts, Benefits and Knowledge Gaps

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Abstract: Industrialization and urbanization have led to an increased accumulation of waste materials that are transformed into a nutrient-rich and high-quality product called vermicompost by the vermicomposting process. Vermicomposting is an ecofriendly and economically favorable biotechnological process that involves the interaction of earthworms and microorganisms. Due to the importance of this process and its great potential in dealing with the consequences of waste accumulation, this review aims to provide key insights as well as highlight knowledge gaps. It is emphasized that there is a great challenge in understanding and clarifying the mechanisms involved in the vermicomposting process. The optimization of the factors affecting the possible application of vermicompost is crucial for obtaining the final product. Information on the composition of bacterial communities, amount of vermicompost, effect on heavy metal content, plant pathogens, diseases and organic waste selection is here recognized as currently the most important issues to be addressed. By answering these knowledge gaps, it is possible to enable wider utilization of vermicompost products.

Keywords: organic waste; vermicompost; bacterial communities; earthworms; optimization

1. Introduction

Over the last few decades' numerous human activities have led to an increased accumulation of waste materials. Therefore, waste management has become an important topic worldwide [1]. When waste materials are discussed, mostly solid waste (SW) is referred to. The overall objective SW management is to deal with waste in an environmentally and economically sustainable way [2]. According to the literature, about 2.01 billion metric tons of solid waste are produced annually, and it is estimated that this number will increase to 3.40 billion metric tons by 2050 [3]. SW includes organic and inorganic materials produced by different sources. There are numerous classifications of SW that are also complex, but research on domestic waste [4], municipal solid waste [5], sewage waste [6], ashes [7], manures [8] and many others in the literature can be found. Global waste, mostly industrial, can also be classified into hazardous and nonhazardous waste [9]. Since the highest percentage is nonhazardous waste, there has been an increasing interest to find an ecofriendly, rapid and financially favorable technique for efficient waste management that is an entry point to sustainable development [10,11].

Vermicomposting is a biotechnological process of composting wide ranges of organic waste [12–14] that includes specific earthworms' species that enhance the waste conversion into a very useful high-quality end product known as vermicompost [15,16]. Vermicomposting involves bio-oxidative processes and the stabilization of organic material just as in composting; except in vermicomposting, this includes interactions between earthworms and microorganisms. The role of microorganisms is the production of enzymes that cause the biochemical decomposition of organic matter, while earthworms contribute to a larger



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Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). microbial population through fragmentation and ingestion of fresh organic material. Besides the above, earthworms also interact with other organisms in the soil and can affect various microflora and microfauna communities [17]. Although vermicomposting and composting have some similarities, there are many significant differences between them, which are highlighted in numerous reviews [18–20]. These differences include the lack of the thermophilic phase in vermicomposting during which pathogens are reduced [6], different requirements of moisture content that are higher for vermicomposting and differences of end-product quality where vermicomposting shows more positive effects on the physicochemical properties of the soil and on plant growth [21,22]. The conversion of industrial waste into vermicompost is important for pollution monitoring and controlling, since vermicompost has potential application in remediation and can be used for the reduction of the waste (Figure 1) [23]. Additionally, vermicompost has many beneficial effects on plants including induction of plant growth and yield (Figure 1). Therefore, it is also important for agriculture and horticulture purposes because it is used as fertilizing material [24] but also in terms of sustainable development.



Figure 1. Conversion of organic waste into compost and vermicompost and the potential uses of vermicompost.

At least 4400 species of earthworms are classified on the basis of their deeding and burrowing strategies into three ecological niches: epigeic, anecic and endogeic. Epigeic species are pigmented, live superficially in the litter layer, form no permanent burrows and feed on decaying organic matter and litter materials; endogeic species live in horizontal burrows at approximately 10–15 cm depth and feed on the organic matter in the soil; and anecic species are relatively large and live in vertical burrows from which they collect dead organic matter on the surface at night [25]. Epigeic species are the most suitable for vermicomposting due to a high affinity for the organic substrate, high rates of consumption and digestion, owing to its tolerance for changes in environmental conditions, short life cycles, high reproductive

rates and easy culturing [26]. According to mentioned characteristics, few species such as *Eisenia fetida* (Bouché), *Eisenia andrei* (Savigny) and *Perionyx excavates* (Perrier) have been used extensively in vermicomposting. Among the above and according to the literature reviewed, *E. fetida* is used more often than others in various studies that include the effect of vermicompost on plant growth, bacterial community size and structure and soil physic-ochemical properties [27–31]. Domínguez et al. [32] and Gómez-Brandón et al. [33] used *E. andrei* in elucidating the impact of vermicomposting on changes in the composition and function of bacterial communities. Furthermore, *Perionyx excavates* is also used extensively in vermicomposting of different materials such as domestic waste [4,14], urban green waste [34] and agriculture waste [14]. Unlike *Eisenia fetida* and *Eisenia andrei* which are temperate, *Perionyx excavates* is the tropical epigeic earthworm.

2. Bacterial Community Structure in Vermicompost

Although earthworms are key players in the vermicomposting process, microorganisms perform the actual biochemical decomposition of organic matter, whether those bacteria are from the soil or the earthworm's gut. The dependent relationship and synergistic actions between earthworms and microorganisms are unquestionable. Namely, due to earthworms' physical activities of substrate aeration, mixing and grinding, they increase the available area for a habitation of microorganisms and affect their structure, composition, activity, abundance and growth rate [29,32]. The end product of vermicomposting is rich in diverse microbial communities such as phosphate solubilizers, N₂ fixers [35], enzymeproducing and plant growth-promoting bacteria [36]. In general, bacterial communities in the soil and their activities affect soil properties and other soil organisms and contribute to the nutrients cycling in nature such as carbon, nitrogen and phosphorus.

Even though there are a lot of data about bacterial succession during vermicomposting [37,38], little is known about bacterial communities. Few studies have contributed to clarifying this topic and characterizing the temporal changes in bacterial communities throughout the process [30,32,33,39]. According to Domínguez et al. [32], during vermicomposting of Scotch broom (Cytisus scoparius), bacterial communities can be classified in three groups—bacteria present in freshly cut Scotch broom (day 0); bacteria that have recently passed through the intestines of earthworms and been excreted (day 14); and bacteria associated with the cast aging process (days 42 and 91). Their results showed that bacterial composition was split between phylum Proteobacteria, Bacteroidetes, Actinobacteria, Firmicutes and Verrucimicrobia. Proteobacteria were most abundant at the beginning of the process, while after the 14th day, their abundance decreased but still remained significant. On the 14th day, other phyla appeared, but their abundance also differed depending the phase of vermicomposting. Similar results showed by Kolbe et al. [39] in vermicomposting of grape marc for 91 days. Significant changes in bacterial community composition were observed at day 7 until day 91, where taxonomic, phylogenetic and functional diversity increased through experiment. In fresh grape marc, compared with results for a fresh Scotch broom, besides Proteobacteria, Kolbe et al. [39] found a high abundance of Firmicutes. When it comes to bacterial diversity and dynamics of bacterial succession, both the starting substrate and the used earthworm species are crucial [32,40]. In both Scotch broom and grape marc, bacterial diversity in the starting material was relatively low. Even though bacterial diversity is generally low in starting substrates and during the first phase of vermicomposting, it significantly increases during the process [32]. Except for bacterial diversity, earthworms can also have a dual impact on microbial abundance, which also depends on a starting material. Comparing Scotch broom and grape marc with other types of substrate such as manure or sewage, differences in bacterial diversity and abundance are expected. Namely, manure or sewage are substrates that are firstly processed by animals, and that kind of already-diverse substrate has a greater bacterial diversity and higher abundance, while the process of vermicomposting can reduce both [41]. Considering bacterial phylum composition during vermicomposting and its detailed analysis, a clear link can be made between specific bacteria and their respective roles which may explain the beneficial properties of vermicompost. Chitrapriya et al. [35] showed that vermicompost produced from cow dung and saw dust contained Bacillus (Firmicutes), Streptomyces (Actinobacteria) and *Pseudomonas* sp. (Proteobacteria) as phosphate solubilizers and Azobacter (Proteobacteria) as nitrogen-fixing bacteria. Domínguez et al. [32] detected the genus *Devosia* (Proteobacteria), which can contribute nitrogen fixation and release plant growth-promoting substances, family *Cellulomonodaceae* (Actinobacteria) and genus *Achromobacter* (Proteobacteria), which produce plant cell degrading enzymes.

In most of the abovementioned studies, the same bacterial phylum appears in vermicompost of different substrates with some exceptions in total phylum number, time of their appearance and dominance of the specific phylum. All these differences can be driven by various factors, not just the type of initial substrate and earthworm species used. Changes in microbial communities are also correlated with changes in the organic carbon source, pH value, which can affect nutrient availability, and changes in the physical properties of the substrate, which can promote the growth of aerobic bacteria [30,33].

3. Effect of Vermicompost on Plant Growth and Yield

Fertilizers have been used since ancient times to increase the height and quality of the crop yield. In recent decades, the improper use of mineral fertilizers has resulted in pollution of soil, water and air and, as a consequence, raised important questions regarding food quality and environmental safety [42]. Accordingly, one solution is to use organic fertilizers, especially vermicompost. Discouraging the use of inorganic fertilizers and their replacement by vermicompost makes vermicompost a significant factor in sustainable agriculture and its future. The characteristics that make vermicompost an effective fertilizer is homogeneity, high porosity, high water-holding capacity, stability, low C:N ratio and the fact that it is an ecofriendly, nutrient-rich material [43–45]. Vermicompost is known to have a wide range of effects on plants, and most of them are beneficial. In general, it can be said that vermicompost improves growth, yield and quality of plants. All beneficial effects of vermicompost include stimulation of root and shoot development, increasing seed germination, leaf area, root branching, fruit yield, nutritional quality, stimulation of plant flowering, affecting the biomass, photosynthetic pigments, photosynthesis and respiration rates [7]. Except for positive effects of vermicompost on plants, it is important to mention vermicompost water extracts also called vermicompost 'teas', which have become increasingly current in recent years and show similar effects as vermicompost [18,31,46].

When generally speaking about improved plant growth and development, in substrate enriched with vermicompost, it is primarily due to the presence of humic acids (HAs) [47–49] and different micro- and macro-nutrients [50], which are converted during vermicomposting into more plant-available forms.

Macronutrients such as nitrogen and phosphorus are more available to plants due to N₂ fixers and phosphate solubilizing bacteria [35]. Considering that phosphorus is often one of the prime limiting factors for plant growth and the least mobile and therefore mostly unavailable to plants compared to other nutrients, phosphate-solubilizing bacteria play an important role in supplying phosphate to plants. The utilization of these bacteria for direct application in agriculture is reviewed by Khan et al. (2007) as a promising strategy with great potential for use in sustainable agriculture.

Suthar et al. [4] found that the content of nutrients such as N, P, K, Ca, Cu, Mg, Fe and Zn is much higher in vermicompost than in farmyard manure, and it resulted in increased growth and yield of garlic (*Allium sativum*). Manivannan et al. [44] showed that the application of vermicompost from sugar mill wastes caused a decrease in pH value both in clay loam and sandy loam soils due to the acidifying effects of organic acids. Decreased pH to values between 6 and 7 can promote the availability of nutrients to the plants and uptake by plants, which results in the better growth of beans (*Phaseolus vulgaris*). Some of the parameters that indicate plant growth and development are closely related to change in photosynthetic parameters. The effect of vermicompost on photosynthetic pigments, photosynthesis and respiration rates is well documented. Usmani et al. [7] reported an

increase in chlorophyll a, chlorophyll b and carotenoids with an increase in the concentration of vermicompost (3, 6, 9, 12, and 15%) in two plant species, *Lycopersicon esculentum* and *Solanum melongena*. According to that, increased plant pigments resulted in a high photosynthetic activity, which can also enhance growth and yield, which is evident through the increase in the weight and length of shoots, the number of leaves, flowers and fruits.

In regards to the nutrients, it is known that nutrient uptake can be affected by HAs through the synthesis and functionality of membrane proteins, especially proton pumps that increase the electrochemical proton gradient across the plasma membrane (PM) [51].

Vermicompost enriched with HAs plays an important role in stimulating plant growth and development. Namely, Gholami et al. [52] determined the effects of HA at 0, 0.3, 0.6 and 0.9 kg ha⁻¹ and vermicompost at 0, 5, 7.5 and 10 t ha⁻¹ on mineral elements N, P, K, Fe, Zn, Mn and Cu uptake and photosynthetic pigment concentrations of chicory. Due to the presence of HAs, the activity of microorganisms in the soil was improved that finally increased N, P and K content in plants. This is an example of 'indirect action' of HAs on plants, while there is another 'direct action' that includes plant hormones [47]. As plant growth hormones are found in an aqueous solution of vermicompost, Arancon et al. [47] hypothesized that hormones such as auxins (indole-3-acetic acid-IAA), which are watersoluble, may adsorb on to humates and become more persistent in soil and thus extend the period of action on the plants.

When it comes to plant hormones, some bacterial species can synthesize them too. Namely, Gómez-Brandón et al. [33] observed an increase in specific genes related to salicylic acid synthesis in grape marc vermicompost, while Domínguez et al. [32] found a general increase in metabolism genes also connected to salicylic acid synthesis in Scotch broom vermicompost. Salicylic acid affects multiple aspects of plant growth and development, but it is also an essential regulator of plant-microbe interactions [53]. Phytohormones are one of the factors that can affect the ability of plants to differentiate cells and tissues into plant organs such as roots and shoots. In support of this, Arancon et al. [31] evaluated different concentrations (1, 2, 5 and 10%) of water extracts from vermicompost on rooting characteristics of stem cuttings. As they found a combination of auxins, cytokinins, GA and HAs in water extracts, they connected it with increased rooting in stem cuttings. Furthermore, Olaetxea et al. [54] showed that both the root plasma membrane H+-ATPase activity and root abscisic acid (ABA) play a crucial role in the root growth-promoting action of SHA (humic acids with a sedimentary origin and extracted from leonardite) in cucumber. Increased H+-ATPase activity, except increasing ABA concentration in roots, mediates an increase in cytokinin concentration and action in shoots. ABA is not the only signal involved in SHA-mediated root growth. This signal pathway is just a part of a much more complex signal network that also includes auxin, NO and ethylene [54–56]. Olaetxea et al. [54] assumed that in all possible signaling pathways connected with root growth that is caused by the presence of Has and reactive oxygen species (ROS) might also have an important role.

Furthermore, bioactivity levels of HAs are not only a result of phytohormones-related effects but also a presence of other plant growth regulatory substances, such as alkamides present in HA. Zandonadi et al. [55] described the effects of N-isopropyldecanamide, the unbound fraction of HA isolated from cattle manure vermicompost, on the PM H+-ATPase activity in maize seedling roots. Namely, PM H+-ATPase activity increased due to higher concentrations of N-isopropyldecanamide which resulted in enhanced root development which was evident from an increase in root dry mass, total length and superficial area.

With the various indirect effects of vermicompost on plants, the suppression of plant diseases is one of the most significant. This is primarily related to earthworms that release coelomic fluids which kill the parasites present in the waste. Plavšin et al. [57] showed antifungal activity of earthworm coelomic fluid extract in in vitro testing. Furthermore, Dominguez et al. [32] observed an increase in salicylic acid and streptomycin synthesis after vermicomposting. Salicylic acid can induce plant pathogen resistance mechanisms, and antibiotic streptomycin has been shown to control bacterial diseases of fruits, vegetables

and crops [58]. Except for the suppression of bacterial diseases, vermicompost can also suppress fungal diseases. Regarding the suppression of fungal diseases, they include the effect of vermicompost on reduced sporulation, reduced growth of pathogenic fungi and, generally, reduced infection [59]. Amooaghaie et al. [60] also reported that vermicompost is an effective biocontrol agent against *Fusarium oxysporum* and *Phytophthora infestans*.

According to most of the known literature, different types of vermicompost induce higher germination rate, plant growth and yield in many plant species such as tomato [27], lettuce [43], cucumber [61], petunia [8], pine trees [62], thyme [60], begonia, sugarcane and mint [31]. However, according to some data, one cannot generalize and speak exclusively about the positive effects of vermicompost [60,63]. Amoogaghaie and Golmohammadi [60] investigated the effect of various cow manure vermicompost (25, 50, and 75%) on the germination, growth and development of thyme. Their results showed that only 25% vermicompost substitution promoted seedling emergence, while other substitutions did not have a beneficial effect. Moreover, in 50% vermicompost substitution the maximum length, fresh and dry weight and photosynthetic efficiency were observed. Similar results observed Atiyeh et al. [27] who showed that vermicompost increased seed germination and growth only to a certain amount of vermicompost substitution, while higher amounts (100%) had negative effects, which were evident in shorter seedlings, fewer leaves and decreased germination. Ievinsh [63] reported that cow manure vermicompost substitution inhibited seed germination or did not have any effect which depended on the concentration of vermicompost (10–100%) and the plant species he used. All negative effects of higher vermicompost concentrations could be due to the induced stress by the high-soluble salt concentration or phenolic compounds from vermicompost [60].

4. The Potential Use of Vermicompost in Remediation

Some of the positive effects of vermicompost on soil, plant growth and development have already been mentioned, but some other potentially positive effects of vermicomposting and vermicompost itself, e.g., remediation, can also be discussed. It is well known that environmental contaminations are mainly caused directly or indirectly by industrialization and urbanization. Among the many pollutants, the most prominent ones are those caused by heavy metals (HMs) and organic ones which represent a serious problem worldwide [9]. Although there are various physical, biological and chemical methods by which these pollutants are removed from water or soil, there has been a need for less aggressive and environmentally friendly methods. As some studies have shown, vermicomposting shows some potential to become such an alternative for an environmentally friendly remediation method [23].

When it comes to HMs, they are nonbiodegradable and tend to enter into food chains and bioaccumulate, which can represent an escalating problem for all living organisms. Many previous studies reported a reduction of HMs after vermicomposting [64–66]. During vermicomposting, it is initially important to mention earthworms and bacteria that can influence HMs availability and bioaccumulation. Earthworms can accumulate HMs into their bodies, which is accompanied by the synthesis of metallothionein that can bind several metals such as Zn^{2+} , Cu^{2+} and Mn^{2+} [67,68]. For example, Liu et al. [69] reported that concentrations of Cu, Ni, Cd, Pb and Zn in vermicompost decreased comparing to initial sewage sludge, while in *Eisenia fetida* tissues, their concentrations increased due to their adsorption. Wang et al. [70] also observed that vermicomposting by Eisenia fetida decreased the total amount of Cu (8.3–17.2%), Zn (5.0–8.7%), Pb (4.9–9.8%), Cd (7.1–15.4%) and As (1.1-9.0%) in the substrate of all treatments, as the total amount of each metal in earthworms increased. On the other hand, bacteria can also contribute to immobilization and reduce the bioaccumulation of HMs. Heavy metals have different adsorption affinities on bacteria due to electronegativity of metal ions with the affinity being higher with greater electronegativity [71]. Bacteria also have the ability to precipitate and alter oxidation states of HMs. For example, some previous studies showed that bacteria present in the soil such as *Bacillus* sp., *Microbacterium* sp., *Serratia* sp. and *Arthrobacter* sp. can reduce

Cr (VI) to Cr (III) by accepting the electron via bacterial enzymatic processes. What is more, Cr can be removed owing to different Cr (III) forms such as calcium chromium oxides [72,73]. In addition to the direct effects of earthworms and bacteria on HMs during vermicomposting, they may also indirectly affect it since the ultimate characteristics of vermicompost are largely influenced by their activity. Mature vermicompost is rich in soluble salts and humic substances that possess different functional groups such as -NH, -OH, -COOH, -CO, etc. [74]. Dissolved organic matter or HAs as its representative can form organometallic complexes with target metal ions. Namely, humic substances from vermicompost can effectively remove HMs due to carboxylic and phenolic groups as coordination sites with metal ions [75]. However, other functional groups also have the ability to bind metal ions. Chen et al. [75] have observed that during the copper-binding process to dissolved organic matter, the carboxyl and polysaccharide groups gave the fastest responses to copper binding followed by phenolic, aryl carboxylic and small amounts of amide and aliphatic groups. Zhang et al. [76] investigated the immobilization effect of vermicomposted sewage sludge for Pb, Cd and Cr in the sediment under simulated in situ conditions, and they also concluded that different humic substances formed organometallic complexes with all three HMs. According to their results, vermicompost can be used as an in situ sorbent for the remediation of sediments that are polluted with HMs. Even though there are many data about creating the complexes between humic substances and HMs, it is not completely clear how, and there is no uniform model for that, especially due to the heterogeneous characters of the organic composition of vermicompost. By contrast to all that was mentioned, there are some data about increasing HMs concentration after vermicomposting [68,77,78]. Studies that observed an increase in HMs after vermicomposting assumed that it is a result of decreased weight and volume after the breakdown of organic matter or it might be related to the excretion of worm castes coupled with HMs [77]. Furthermore, Wang et al. [66] concluded that some results could be explained if one considers the duration of the experiment/vermicomposting process and the time when the earthworms begin to secrete HMs into the raw material. What is not questionable is that earthworms and bacteria that are part of the vermicomposting process and changes on physicochemical properties in substrates affect the mobility and availability of HMs [68].

5. Disease and Pest Control by Vermicompost

The rapid growth of the world's population requires much higher agricultural production to meet basic human needs. On the other hand, world agriculture is facing many problems in crop production, among which are plant diseases and pests [79]. The application of chemicals such as pesticides gives positive results in regard to the control of pests, but they also cause several negative side effects such as environmental pollution, disruption of the soil's natural fertility and the destruction of beneficial organisms [80,81]. To overcome problems of harmful organisms and diseases, in recent years, vermicompost has been mentioned as a key alternative in the fight against plant diseases, pests and pathogens [82]. With the various indirect beneficial effects of vermicompost on plants, the suppression of plant diseases and pests is one of the most significant. It is important to emphasize that vermicomposting contributes not only to the reduction of plant but also human and animal pathogens.

Namely, organic wastes, such as animal byproducts that can be vermicomposted and used as fertilizers, may contain pathogenic microorganisms [83–85]. Roubalova et al. [83] observed the reduction of pathogens such as *Escherichia coli*, *Enterococcus* spp., and thermotolerant coliform bacteria in grape marc during vermicomposting. There are several possible ways by which earthworms contribute to the reduction of pathogens including bacteria, fungi and many others. They include a reduced-oxygen environment inside the gut and the presence of intestinal enzymes and coelomic fluids, which kill the parasites present in the waste [57,83]. Monroy et al. [86] reported a decrease in the number of nematodes in a pig slurry after the passage through the earthworm's gut. The decrease occurred due to the digestion of nematodes by the proteolytic activity of enzymes present in the

earthworms' gut. When it comes to coelomic fluids, it is well known that they possess antimicrobial, proteolytic, hemolytic and antifungal effects [57,87]. Plavšin et al. [57] showed that coelomic fluid extracts of two earthworm species, *Dendrobaena veneta* and *Eisenia fetida*, negatively affected phytopathogenic fungi *Fusarium oxysporum* in vitro conditions. They concluded that earthworms might negatively affect fungal growth by ingestion and by contact as well. Although some plant pathogens are removed during earthworm digestion, vermicompost, as a final product of vermicomposting, is a true modulator not only of plant growth but also of disease and pest suppression [88]. The application of vermicompost for the suppression of different soil-borne phytopathogens has grown significantly in recent years [89–91].

Because bacterial communities change greatly during vermicomposting, vermicompost has a significantly different bacterial structure than the initial material. Vermicompost contains beneficial microorganisms such as bacteria, fungi and actinomycetes, which can improve overall plant growth, but also antagonistic microorganisms, which mediate the control of diseases and pests [92,93]. Liu et al. [92] isolated 374 bacterial strains from vermicompost made from fresh cow dung of which 28 strains showed antagonistic activity against Fusarium oxysporum f. sp. cucumerinum (FOC). FOC is a fungal pathogen that causes enormous damage to cucumbers worldwide [92]. Similarly, suppressions of Fusarium oxys*porum* and *Phytophthora infestans* have also been reported by vermicompost treatment [32]. It is important to emphasize that the influence of vermicompost on pathogens depends a lot on the type of initial substrate [94]. Szczech and Smolinska [94] showed that vermicompost from animal manure reduced the infection of tomato seedlings by Phytophthora nicotianae, while vermicompost from sewage sludge did not protect seedlings from infection. The influence of vermicompost on various pathogens also depends on the type of earthworms, i.e., it depends on the morphological and physiological characteristics of the digestive system of earthworms [9]. Regarding the suppression of fungal diseases, they include the effect of vermicompost on reduced sporulation, reduced growth of pathogenic fungi and, generally, reduced infection [17]. Except for the suppression of fungal diseases, vermicompost can also suppress bacterial diseases and pests. Dominguez et al. [15] observed an increase in salicylic acid and streptomycin synthesis after vermicomposting. Salicylic acid can induce plant pathogen resistance mechanisms and antibiotic streptomycin has been shown to control bacterial diseases of fruits, vegetables and crops [16]. Furthermore, vermicompost can manage pests such as mites (Tetranychus urticae), mealy bugs (Pseudococcus sp.), aphids (Myzus persicae) [95], corn earworm (Helicoverpa zea) [96], nematode (Meloidogyne incognita) [97], chili pest (Polyphagotarsonemus latus) [89], etc. Arancon et al. [95] tested the capacity of food waste vermicompost on reduction of three arthropod pests populations and damage to cucumbers, tomatoes, bush beans, eggplants and cabbage plants. Besides noticing the reduction in arthropod populations, pest damage and reproduction, they also noticed that vermicompost made the plants less attractive to the pests. Jangra et al. [89] also recorded a reduction in population, and a number of chili pest eggs after the vermicompost was applied in a rate of 5 t/ha. They hypothesized that a possible reason for the suppression of pests was due to soluble micro- and macro-nutrients in vermicompost. It is correlated with the conclusion of Arancon et al. [95]. Possible mechanisms can also include the production of phenolic compounds by the plants after applications of vermicomposts, making the tissues unpalatable or even the presence of chitinase enzyme in vermicompost that helps in controlling arthropods [98,99].

6. Knowledge Gaps

Vermicomposting is a process that has been intensively studied for years and has become significant and frequent topic. Numerous papers are describing its mechanism and performance, but each highlights different aspects [16,23,82,100]. Although numerous studies have been conducted on the topic of vermicomposting and each of them has contributed to understanding the role of vermicompost, there are still unknowns that need to be additionally explored to maximize the potential of vermicompost and to recoup the

process itself according to specific needs (Figure 2). The knowledge gaps mentioned and explained in this review are the ones identified to be the most important and which should be assessed first. Following the investigation of these topics and revealing the mechanisms lying behind, additional research questions will have to be investigated.



Figure 2. Even though many facts about vermicompost are known, there are still knowledge gaps that need to be additionally explored to maximize the potential of vermicompost.

6.1. Composition of Bacterial Communities

Additional knowledge on the composition of bacterial communities and their specific roles is required. Although some data exist, additional investigation on the dynamics of bacterial succession and interactions related to earthworm species used for vermicomposting would enable better optimization in the context of selection of specific bacteria in combination with particular earthworm species in order to obtain final products with preferred characteristics. The knowledge on the microorganisms present both in the soil and in the earthworm gut and their function in the process of decomposition of organic matter are of immense importance. The decomposition of organic matter during vermicomposting takes place over a period of time and can be divided into several phases. In these phases, changes in microbial community composition occur, and the investigation of these fluctuations would enable better understanding of synergistic effects occurring between earthworms and microorganisms. Finally, in-depth research on the bacterial communities that participate in the active phase of vermicomposting would enable the maximum use of

this process and, based on the initial substrate and microorganisms, determination of the properties of the final product.

6.2. Amount of Vermicompost

Despite all the above, it is obvious that vermicompost still has a beneficial role for plants depending on its amount added to the soil. In addition to the amount of vermicompost, its physical, chemical and biological characteristics also determine the effects on the plant. The process of vermicompost formation, its age, and the earthworm species used, as well as the plant species itself, its requirements and genotype are also significant factors to consider. When it comes to the amount of vermicompost, it is not fully understood how after a certain amount of vermicompost, all the positive effects disappear. Most of the literature listed possible causes such as overdose with hormone-like molecules, stress caused by high nutrient concentration, competition for nutrients with other soil organisms or some physical changes of soil than can negatively affect plants [101]. Overall, the mechanisms by which high amounts of vermicompost affect plant growth and development should be investigated more. Bouin et al. [101] in their meta-analysis suggested a range between 30 and 50% amount of vermicompost in the growing media as one of the better conditions for observing the effect of vermicompost research that would certainly contribute to understanding the same is the examination of the molecular and biochemical mechanisms involved in the plant's response to certain amounts of vermicompost. Generally, it involves primarily plant antioxidative and oxidative status.

6.3. Effect on Heavy Metal Content

Vermicompost is just one of many factors affecting the bioavailability and mobility of HMs in the soil; thus, apart from studying all of them, the impact of vermicompost is especially needed. When it comes to the potential of vermicomposting in reduction of HMs, Swati et al. [102] concluded that future research should be based on bioavailable fractions of HMs and on determining the impact of speciation and ecological classification of earthworm on the fraction redistribution. Although many more studies are needed to clarify the model of the effect of vermicompost on HMs, it is certain that positive effects exist and that vermicompost can be used under certain conditions for heavy metal remediation. The question is "How exactly?" How vermicomposting affects the content of HMs, their mobility and bioavailability depends on its use in further research. In this case, contrary data on the impact of vermicomposting on HMs open new questions and possibly new potential roles of vermicompost. If it cannot be used directly and if it increases the mobility and bioavailability of metals in the soil, it can still be used in remediation, but indirectly. Specifically, it could be used in phytoremediation allowing plants to increase their accumulation as shown by Chand et al. [103] and Chand et al. [104]. Consistent with this possible role, it could also play a role in biofortification. Some of HMs such as Zn is an essential element for all living organisms. Some regions in the world have Zn-deficient soils which are connected with Zn deficiency in humans that can cause serious health issues. In that area, the main aim is to enrich the soil with Zn to increase its accumulation in crops to finally meet human needs for Zn. Sengupta et al. [105] investigated the potential of vermicompost through its Zn and Fe enrichment for augmenting the soil quality as well as increasing the Zn and Fe bioavailability in the grain. It would be interesting to do comparative studies with ordinary soil and soil enriched with vermicompost to the ultimate enrichment of crops with specific essential metals

6.4. Organic Waste Selection

During the process of vermicomposting a wide range of organic wastes can be used. Considering that build up and inappropriate disposal of urban waste can pose serious problems, the reduction of this waste by the production of compost fertilizer from biodegradable waste could reduce environmental problems and help improve waste management. Additionally, byproducts in agriculture, forestry and food production, especially waste in fruit and vegetable processing, leaves, grass and wood waste from parks, represent a potential source for vermicomposting. Considering the characteristics of the initial substrate, i.e., organic waste, it could be possible not only to reduce the waste but also to produce components for various substrates that could be later used for growing seedlings. Although some research has been performed on different types of organic waste used in vermicomposting, there is no comprehensive study that would provide sufficient information on which type of organic waste should be selected for obtaining final product with specific characteristics. The investigation of the relationship between initial substrate and final product characteristics would provide important information for waste management. In addition, the research of the possibilities on exploitation of the final product could have a great potential for use in sustainable agriculture.

7. Conclusions

From this review, one of the things that can be concluded is that there is a great challenge in understanding and clarifying the mechanisms involved in the vermicomposting process. As pointed out through this review, the most urgent questions to be answered relate to the composition of bacterial communities, amount of vermicompost, effect on heavy metal content, plant pathogens, diseases, and organic waste selection. Namely, the possible application of vermicompost products certainly depends on many factors, and with their optimization, it would be possible to influence the characteristics of the final product and consequently better exploit vermicomposting process. Vermicomposting has a great potential to process a wide range of wastes produced in agriculture, food processing, sewage treatment, etc., and generate high-quality end products that can have multiple uses. Vermicomposting involves the "cooperation" between earthworms and microorganisms during a very complex biological process. In addition, there is a possibility of vermicompost application in pollution reduction, which is for sure a topic that should be immediately addressed. Considering that, there are still many unknowns that need to be investigated and optimized in order to use vermicompost products in the context of sustainable agriculture. By answering the current knowledge gaps, it will be possible to increase the understanding of variables and parameters crucial in the process of vermicomposting and will enable wider utilization of vermicompost products.

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