Fertilization of Microbial Composts

Subjects: Agriculture, Dairy & Animal Science

Contributor: Temoor Ahmed , Muhammad Noman , Yetong Qi , Muhammad Shahid , Sabir Hussain , Hafiza Ayesha Masood , Lihui Xu , Hayssam M. Ali , Sally Negm , Attalla F. El-Kott , Yanlai Yao , Xingjiang Qi , Bin Li

Microbial compost plays a crucial role in improving soil health, soil fertility, and plant biomass. These biofertilizers, based on microorganisms, offer numerous benefits such as enhanced nutrient acquisition (N, P, and K), production of hydrogen cyanide (HCN), and control of pathogens through induced systematic resistance. Additionally, they promote the production of phytohormones, siderophore, vitamins, protective enzymes, and antibiotics, further contributing to soil sustainability and optimal agricultural productivity.

biofertilizer | plant diseases | compost | nutrient transformation | PGPR

1. Introduction

In recent years, global food security has been increasingly threatened by the combination of population increase and the scarcity of limited arable land worldwide [1][2]. Consequently, the need to boost crop productivity has become a significant challenge in order to meet the demands of a continuously increasing global population [3]. To enhance crop productivity, various chemical fertilizers have been extensively employed worldwide; however, this widespread use has led to the deterioration of both human health and environmental ecology with significant severity [4][5]. Biofertilizers offer a promising solution in order to counteract the harms associated with chemical fertilizers. They are an essential component of integrated nutrient management, contributing significantly to crop output and food security in the agricultural sector [6][7]. Biofertilizers consist of one or more beneficial microbes capable of colonizing the interior or exterior of plants after soil application, as seeds, or as direct exposure on the plants. This colonization facilitates the enhancement of nutrient supply to the host plant, effectively promoting its growth [8][9]. These microbe-containing fertilizers improve the soil fertility through different mechanisms including atmospheric nitrogen fixation, solubilization of unavailable nutrients (such as phosphate, zinc, potassium, and iron), and synthesis of phytohormones [10]. Thus, the biofertilizers improve soil fertility and crop yield by harvesting the natural biological system of nutrients and recycling them [11]. The efficiency and efficacy of biofertilizers has remained controversial in terms of their application in the field and their potential to replace the chemical fertilizers, mainly due to the heterogeneous nature of soil, adaptability to harsh ecological conditions, and unsuitable formulations and carrier materials [12]. Thus, if a nutrient-rich carrier material with potential to facilitate microbial growth is used, outcomes from biofertilizers can be substantially enhanced and the use of chemical fertilizers can be completely or partially cut down. Nowadays, as a result of intensive agricultural activities, a huge amount of organic waste is generated by agricultural fields, and the disposal of this poses difficulties [13].

Production of nutrient-rich compost from agricultural waste has been emerging as an alternative way of disposal [14]. A dark brown or black earthy matter, rich in micro- and macronutrients and produced as a result of aerobic decomposition of biodegradable waste is known as compost [15]. Compost not only enhances the soil fertility in terms of micro- and macronutrients, it also improves the soil architecture by improving water- and air-holding capacity for better root growth. Moreover, compost can play an important role in the bioeconomy because its production does not depend on finite inputs [16]. This technique of waste disposal has proved to be very economic, as it enhances plant nutrient uptake, soil organic matter content, crop yield, and soil biophysical parameters [13][17]. The application of compost has been proven beneficial, as it has good impact on environment and soil quality [18].

Composting is the process in which organic materials like food scraps, leaves, twigs, lawn clippings, wood waste, and other organic matter are decayed by the soil microorganisms under controlled ambiance [15][19]. To carry out the decomposition process, either a pit can be dug in the ground, or the process can be conducted in special vessels called compost bins [20]. Certain factors, including temperature, proper aeration, pH, the quality and quantity of feedstock, etc., must be considered before initializing the process of composting to make it more efficient and reliable [15]. Another key factor to be considered is the ratio between carbon and nitrogen (C/N), which plays an essential function in the composting process. The application of compost enhances the physico-chemical properties of the soil and also exerts a positive impact on the soil’s microbial diversity [21]. The widespread adoption of compost in agriculture faces constraints due to its extended time of action and comparatively reduced nutrient supply to crops when compared with chemical fertilizers [17]. Various reports have been published on the composting of agricultural feedstock and its potential application in improving soil fertility and plant growth [22][23]. Moreover, the potential role of different phytobeneficial microbial communities to the process of composting has also been elucidated by several researchers around the world [24][25].

2. Biofertilizers and Their Advantages

Agricultural productivity is decreasing continuously due to nutrient deficiency in the soils and the growth of obnoxious weeds and pests [26]. Conversely, the production cost has been raised over the last two decades. As a result of these factors, the growth rate in agriculture is falling behind the rapid pace of population growth [27][28]. The population explosion around the globe makes the use of chemicals fertilizers for improving crop production in order to meet food requirements inevitable [29]. Frequent soil tillage, chemical fertilizers, and narrow crop rotations are some of the intensive agricultural techniques that increase production in a short time. However, over time, these techniques have led to a decline in soil organic carbon, soil aggregation strength, and biodiversity, consequently reducing the productivity of field crops. Additionally, they contribute to air and groundwater pollution [30][31]. In this scenario, the biofertilizers have a great potential to improve soil fertility, thus reducing the need for the application of chemical fertilizers. Biofertilizer-mediated agricultural practices also result in crops with improved yield [32][33].

Biofertilizers utilize beneficial microorganisms to optimize plant growth by increasing nutrient supply, effectively enhancing overall nutrient availability, and promoting healthier and more robust plant development [34][35]. Generally, the potential of different beneficial microbes, including nitrogen fixers, phosphorus solubilizers, potassium solubilizers, iron mobilizers, as well as the microbes capable of producing phytohormones, is utilized during biofertilizer synthesis which improves the nutrient profile of the soil [36][37]. Subsequently, the microbe-oriented nutrient recycling through biofertilizers enhances the soil organic matter content and maintains the soil health and sustainability, which is ultimately followed by healthy plant growth. Several bacterial species, known as plant-growth-promoting rhizobacteria (PGPR), such as *Azotobacter* spp., *Escherichia coli*, *Pseudomonas* spp., and *Bacillus* spp., and arbuscular mycorrhizal fungi (AMF), such as *Glomus versiforme*, *Aspergillus awamori*, *Glomus macrocarpum,* and *Sclerocystis coremioides,* are often exploited in broad spectrum biofertilizers without causing any negative chemical influence on the soils [38][39][40]. Moreover, co-inoculation of PGPR and AMF also results in enhanced plant growth, nutrient uptake, disease tolerance, and resistance to abiotic stress. For example, co-culture of *Rhizobium*, *Azotobacter,* and vesicular arbuscular mycorrhiza (VAM) as biofertilizer enhanced the straw and grain yield when applied to wheat plants along with rock phosphate as a phosphate source [41]. Similarly, a mixed culture comprising *Thiobacillus thioxidans*, *Bacillus subtilis*, and *Saccharomyces* sp. was found capable of converting micronutrients into soluble forms such as Mn, Zn, Fe, etc., and making them available to plants [33]. *Trichoderma* spp. are also known to improve the tolerance of plants to biotic and abiotic stresses by producing enzymes that can detoxify harmful chemicals and by increasing the production of stress-response proteins in the plant [42]. For example, *Trichoderma harzianum* inoculation improved tomato plants' tolerance to chilling stress by enhancing physiological, biochemical, and molecular responses [43]. The biofertilizers that achieve nitrogen fixing, i.e., potassium- and phosphate-solubilizing bacterial strains, significantly improve the growth, production, and qualitative characteristics of food crops [44]. Hence, these microbial-based fertilizers can significantly contribute to the establishment of sustainable agriculture systems, playing a pivotal role in achieving this goal.

Overall, the utilization of biofertilizers has been in practice for a considerable period due to their eco-friendly nature and superior cost-efficiency compared with chemical fertilizers. The biofertilizers can also be used to convert complex organic materials into simple compounds, followed by a change in the color and texture of the soil [45][46]. They have the capability to enhance the crop yield by 25–30% and can help the soil fight against dehydration and other soil-borne illnesses [15]. Therefore, to promote agricultural productivity, it is essential to acknowledge the application of biofertilizers [47][48].

3. Microbial Compost

Agricultural waste is now emerging as a compelling and cost-effective resource that can provide organic matter and essential plant nutrients to the soil, effectively supporting crop production [49]. However, raw organic waste cannot be directly applied because it is unsuitable for land and agricultural crops [50]. Hence, composting stands out as one of the most favorable, straightforward, and cost-effective methods employed to treat this type of wastes [51][52]. Compost can be locally produced on the farm and is an attractive technique of waste disposal. It is can recover valuable plant nutrients and improve the soil's biophysical characteristics, soil organic matter, and crop yield [53][54]. As the nutrients in compost are slowly released depending upon the microbial biomass, the gradual nutrition availability for the plants is ensured [55]. Thus, the utilization of microbial compost aids in preventing nutrients leaching into groundwater and significantly increases soil productivity in the long term. The soil quality can be enhanced by repeated compost applications, which result in the enriching of microorganisms that are beneficial to the soil, an increased total carbon content, an enhanced cation exchange capacity, and a reduction in the abundance of plant-parasitic nematodes [56]. The use of pesticides and herbicides also decreases due to the improved plant resistance against diseases as a result of compost application [57]. The application of compost, along with certain soil microorganisms such as PGPR and AMF, has been proven to effectively boost soil fertility and health [58].

3.1. The Composting Process

The process of controlled decomposition of organic material like agricultural residues is known as composting [59]. A composting process requires the synergistic action of the natural forces that decompose the organic waste into the organic fertilizer to occur in a safe way [60]. The primary raw materials utilized for composting include agricultural waste such as fruit and vegetable waste, domestic kitchen residues, various crop residues (e.g., stover, cobs, and leaves), and different types of manure, e.g., cattle and poultry [61]. Both aerobic and anaerobic bacteria are involved in the composting process. For better a understanding of the degradation processes that occur in compost, characterization and identification of microorganisms is necessary in the composting process. Common PGPR, like *Azotobacter* spp., *Pseudomonas* spp., *Escherichia coli*, and *Bacillus* spp., and some AMF, such as *Aspergillus awamori*, *Glomus macrocarpum,* and *Sclerocystis coremioides,* were found to be involved in the decomposition process [62][63]. These microorganisms utilize amino acids, sugars, and lipids present in the feedstock as their energy source [64][65]. Composting offers numerous benefits beyond providing a significant release of various nutrient elements for plants. It contributes to soil conditioning, facilitates efficient manure handling, reduces the risks associated with different pollutants and weed seeds, and promotes pathogen destruction through a high-temperature composting processes [66]. A schematic diagram of the composting process has been presented in **Figure 1**.

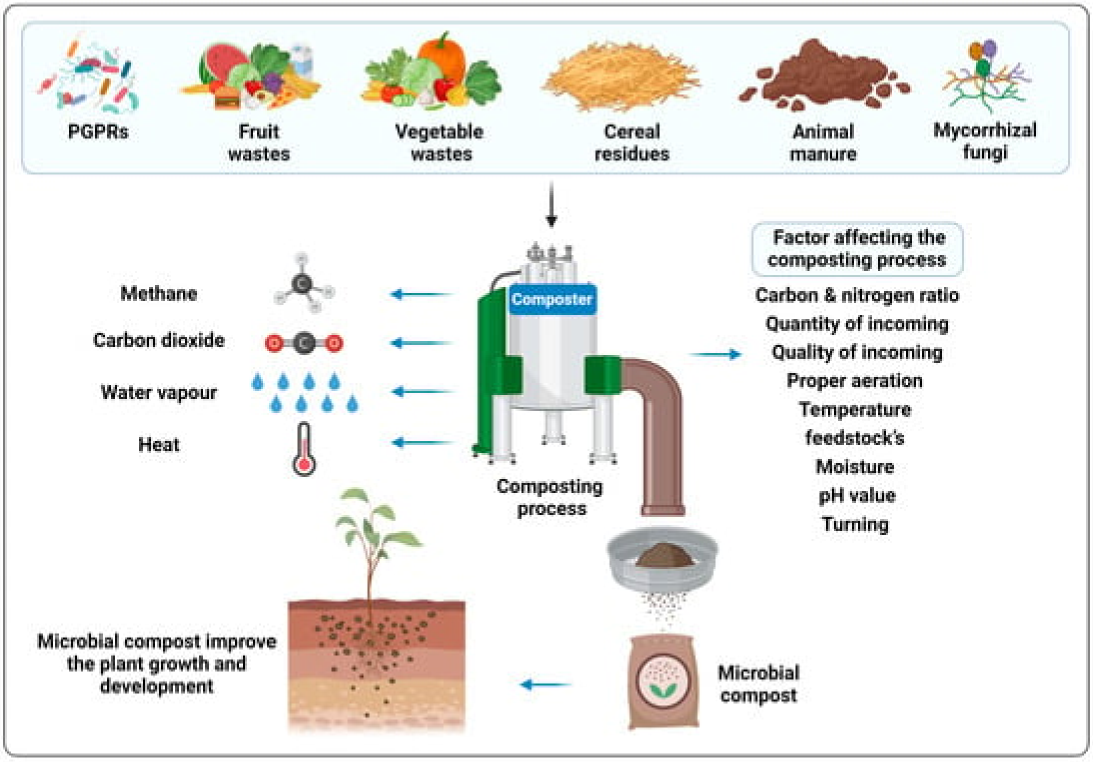

Figure 1. Schematic representation of the composting process.

3.2. The Biochemistry of Composting

The compost feedstock is often rich in organic compounds that are rich in components like carbon (C), hydrogen (H), oxygen (O_2), and nitrogen [67]. The lignin, sugars, fats, cellulose, and proteins that are important components of agricultural raw material facilitate the decomposition of organic compounds during the process of composting. These components become progressively more oxidized and form molecules with more functional groups that have, however, a lower molecular weight during the aerobic decomposition [68]. The product obtained after the decomposition of organic matter is known as humus. In addition, the biodegradation occurs under both anaerobic and aerobic circumstances, but the composting process proceeds excellently under aerobic conditions [69]. Many microbes can perform their function in the absence of O_2, but the process of anaerobic respiration is less energy-efficient and it utilizes chemical species like sulfate, carbon dioxide, nitrates, sulfur, and oxidized metal ions. Hence, to suppress the development of anaerobic conditions, artificial aerobic conditions should be introduced in the compost pile through pulling or pushing the air [70][71].

3.3. Microorganisms Involved in Plant Growth and the Composting Process

The composting process can be characterized as the biodegradation of organic waste into useful products under controlled ambiance. These products are applied to the soil, and they effectively enhance the physico-chemical properties of the soil [72][73]. The biodegradation of organic waste is accelerated by diverse microbial species belonging to different microbial groups, namely, bacteria, actinomycetes, and filamentous fungi. The bacterial species belonging to the genera *Pseudomonas*, *Bacillus*, *Paenibacilus*, and *Enterobacter* were found to be the most abundant microorganisms, having a very high population density of 3.0×10^8 CFU/g throughout the composting process, followed by actinomycetes (mainly the species of genus *Streptomyces*, *Nocardia*, *Micromonospora*, *Thermomonospora Dactylosporangium,* and *Kibdelosporangium*). The members of filamentous fungi that drive the composting process mainly belong to the genus *Aspergillus* and have a low population density (i.e., $1.2–1.6 \times 10^8$ CFU/g) [72].

A group of specific microorganisms which positively influences plant growth are PGPR and AMF [48][74]. A number of PGPR and AMF, along with their potential roles in plant improvement, are presented in **Table 1**. These microbes belong to many genera, including *Xanthomonas*, *Agrobacterium*, *Streptomyces*, *Alcaligenes*, *Cellulomonas*, *Arthrobacter*, *Amorpho sporangium*, *Bacillus*, *Pseudomonas* sp., *Azotobacter*, *Actinoplanes*, *Rhizobium*, *Erwinia*, *Bradyrhizobium*, *Enterobacter*, *Rhizophagus irregularis*, and *Glomus intraradices* [6]. Generally, the microorganisms that are used as BF are potassium solubilizers, phosphorus solubilizers, nitrogen fixers, and phytohormone producers [75]. Nitrogen-fixing microbes convert atmospheric N_2 to ammonia [76]. Some microorganisms belonging to the *Ectorhizospheric* strains and *Endosymbiotic rhizobia* have been defined as efficient phosphate solubilizers [7][77]. The most potent strains from bacterial genera that solubilize phosphorus are *Pseudomonas*, *Bacillus*, *Enterobacter*, and *Rhizobium* genera [9][78]. Similarly, numerous PGPR species belonging to different genera, namely, *Bradyrhizobium*, *Pseudomonas*, *Rhizobium*, *Agrobacterium*, *Klebsiella*, *Enterobacter*, *Azotobacter*, and

Bacillus, are best known for their phytohormones production potential. These microbe-oriented phytohormones have an effective role in plant growth stimulation.

The ability of PGPR to solubilize potassium rock by secreting organic acids has also been investigated. A number of bacterial strains, including *Burkholderia* sp., *Bacillus mucilaginosus*, *Ferrooxidans* sp., *Paenibacillus* sp., *Pseudomonas* sp., *Bacillus edaphicus*, and *Acidothiobacillus* sp., are PGPR that solubilize potassium-bearing minerals, thereby releasing the potassium in the form that is available for plants [79]. Therefore, utilizing PGPR as biofertilizers to enhance agriculture can reduce the dependence on agrochemicals and promote sustainable crop production (**Figure 2**).

Table 1. Some PGPR and AMF strains involved in plant growth promotion.

Chemicals	Microorganisms	Beneficial Effects	References
	Direct Mechanism		
Nitrogen fixation	*Bradyrhizobium japonicum*, *Glomus macrocarpum*, *Azotobacter vinelandii*, *Bacillus*, *Rhizobium*, *Beijerinckiaderxii*, *Klebsiella pneumoniae*, *Enterobacter cloacae*, *Citrobacterfreundii,* and *Pseudomonas putida*	The conversion of atmospheric N_2 into plant-utilizable forms triggers improvement in plant development and yield	[80][81][82][83][84][85]
Phosphate solubilization	*Penicillium brevicompactum*, *Aspergillus niger*, *Pseudomonas striata*, *Enterobacter*, *Erwinia*, *Bacillusmegaterium*, *Ochrobactrumanthropi*, *Bacilus*, *Beijerinckia*, *Burkholderia*, *Rhizobium,* and *Serratia*	Solubilizing the inorganic phosphorus from insoluble compounds and making them available to the plants	[86][87][88][89][90]
Potassium solubilization	*Aspergillus niger*, *Aspergillus terreus*, *Acidothiobacillus* sp., *Bacillus edaphicus*, *Ferrooxidans* sp., *Bacillus mucilaginosus*, *Pseudomonas* sp., *Burkholderia* sp., and *Paenibacillus* sp.	Solubilizing potassium rock by producing and secreting organic acids and making them available to the plants for growth and development	[79][91][92][93]
Zinc mobilization	*Beauveria caledonica*, *Hymenoscyphus ericae*, *Oidiodendron maius Pennisetum glaucum*, *Gluconacetobacter diazotrophicus*, *fluorescent pseudomonads*, and *Bacillus* sp.	Solubilizing the insoluble Zn into soluble form and hence having efficient role in plant growth and development	[94][95][96][97][98][99]
Production of phytohormones	*Paecilomyces formosus*, *Asprgillus fumigatus*, *Fusarium proliferatum Azotobacter*, *Arthrobacter*, *Azospirillum*, *Pseudomonas*, *Bacillus*, *Acinetobacter*, *Flavobacterium*, *Enterobacter*,	Play an important role as regulators of growth and development of plants	[100][101][102][103][104][105]

Chemicals	Microorganisms	Beneficial Effects	References
	Micrococcus, *Agrobacterium*, *Clostridium*, *Rhizobium*, and *Xanthomonas*		
Siderophore production	*Aspergillus fumigatus*, *Glomus etunicatum*, *Glomus mossae*, *Trichoderma* spp., *Pseudomonas fluorescens*, *Rhodococcus*, *Acinetobacte*, and *Pseudomonas putida*	Solubilize and sequester iron from the soil and then provide it to the plant cells	[86][106][107][108][109]
Exopolysaccharides production	*Azotobacter vinelandii*, *Bacillus drentensis*, *Enterobacter cloacae*, *Rhizobium* sp., *Agrobacterium* sp., and *Xanthomonas* sp.	Plays a pivotal role in increasing the number of soil macropores, aggregating rhizospheric soil particles, and maintaining water potential	[110][111]
	Indirect Mechanisms		
Hydrogen cyanide	*Alcaligenes*, *Aeromonas*, *Rhizobium*, *Pseudomonas,* and *Bacillus* sp.	Powerful inhibitor of many metal enzymes, especially copper-containing cytochrome Coxidases	[112][113][114]
ACC deaminase activity	*Gigaspora rosea*, *Achromobacter*, *Azospirillum*, *Pseudomonas*, *Enterobacter*, *Bacillus*, and *Rhizobium*	Plants were able to tolerate environmental stresses by keeping a normal amount of ethylene in their root zone	[115][116][117]
Induced systemic resistance	*Trichoderma virens*, *Pseudomonas,* and *Bacillus* spp.	Induced resistance is the state of an enhanced defensive ability developed by plants when appropriately stimulated	[118][119][120][121]
Production of vitamins	*Glomus aggregatum*, *Glomus viscosum*, *Azotobacter vinelandii*, *Azospirillum brasilense*, *Azospirillum* spp., *Pseudomonas fluorescens*, *Rhizobium leguminosarum*, *Rhizobium etli*, *Sinorhizobium meliloti*, *Mesorhizobium loti*, and *Bacillus subtilis*	Facilitate the production of essential compounds for plants and bacteria, induce resistance against pathogens, and directly promote plant growth	[122][123][124]
Production of protective enzymes	*Aspergillus niger*, *Glomus* spp., *Bacillus*, *Burkholderia*, *Enterobacter*, *Pseudomonas*, *Serratia,* and *Staphylococcus*	May have a dramatic effect on the cycling of nutrients such as phosphorus, nitrogen, and sulfur	[125][126][127]

Chemicals	Microorganisms	Beneficial Effects	References
Production of antibiotics	*Pseudomonas*, *Bacillus,* and *Azotobacter*	Prevent the detrimental effects of pathogens on plants through production of inhibitory substances	[128][129]
Volatile organic compound (VOCs)	*Bacillus amyloliquefaciens*, *Bacillus subtilis*, *Pseudomonas fluorescens*, *Bacillus mojavensis*, *Trichoderma* spp., *Trametes gibbosa*, and *Trametes versicolor*	VOCs have a significant role in the plant growth promotion and suppression of plant diseases	[130][131][132][133]

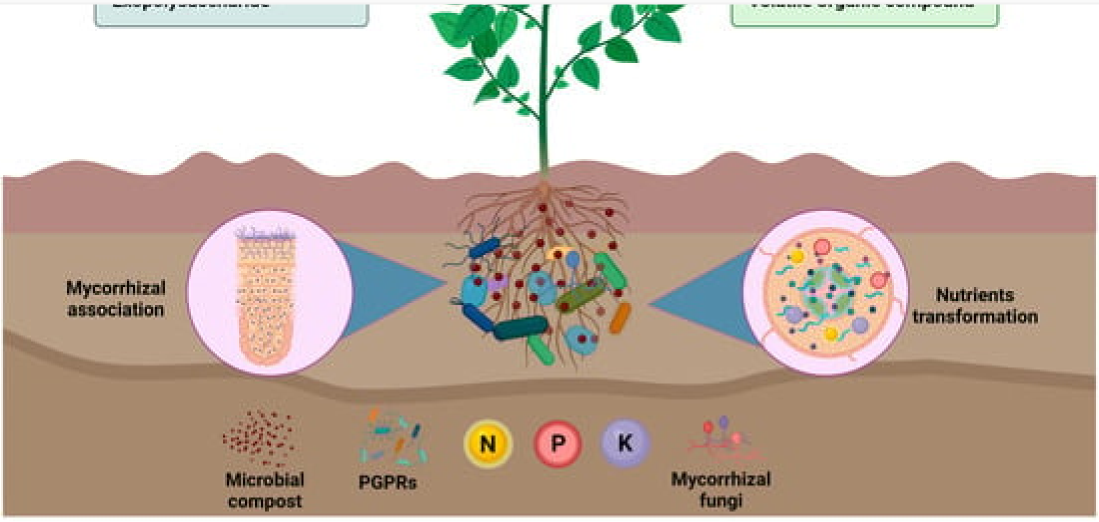

Figure 2. Schematic representation of the compost-based biofertilizers. Mycorrhizal fungal filaments and plant-growth-promoting rhizobacteria in the soil act as to support the development of the plant root system and are more effective at water and nutrient absorption than the roots themselves. PGPR and AMF also explore the soil and reach places unattainable to roots and increase nutrient uptake by plants from the soil. Their effects on plant growth through two different mechanisms, such as direct mechanism and indirect mechanism, are illustrated.

4. The Formulation of the Microbial Compost-Based Biofertilizers

Enriching compost with nutrients, beneficial bacteria, and AMF is a key strategy for improving its nutritional value and enhancing its positive effects on plant growth [134]. By establishing a mutualistic relationship, soil microorganisms and plants work together to facilitate nutrient uptake without disrupting the overall physico-chemical or biological equilibrium of the system. Endophytic PGPR, for example, resides within the plant roots, positively impacting the plants through the secretion of phytohormones, nitrogen fixation, enhanced phosphorus uptake, and the solubilization of inorganic phosphates. This cooperative partnership promotes healthier plant growth and fosters a sustainable ecosystem [135][136]. In general, supplementation of compost with different types of nutrients as well as its bioaugmentation with potential PGPR and AMF strains can lead to value addition in BF technology. Thus, such compost-based biofertilizers need to be added in future long-term farming strategies in order to make the farm yield more sustainable and cost-effective. For this purpose, the compost can be developed through natural processes followed by adding the inoculum of known PGPR or AMF strain(s) at an optimal population density. However, the survival of PGPR or AMF strain(s) in the compost and their synergistic effect, along with natural microflora of compost, are vital factors, which need to be assessed before developing compost-based biofertilizers.

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