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Effect of Microbes in Enhancing the Composting Process: A Review

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Review Article

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ABSTRACT

The increase in global population and the resulting economic activity have led to major environmental problems such soil, air, and water pollution. This rise in population growth has resulted in increased use of chemical fertilizers to boost agricultural production resulting in loss of microbiological and physicochemical equilibrium of soil. These factors have led to an increased need for eco-friendly agricultural products that help to enhance the soil's physical, chemical, and microbiological characteristics and, in turn, provide nutrients for plants. Composting has emerged as the preferred method for treatment of organic wastes in order to produce a final, sterilized product that can be used as an organic amendment. Different organic substances are converted into more stable molecules during the aerobic, microorganism-mediated, solid-state fermentation process known as composting. One effective strategy for accelerating the biotransformation of organic materials during the composting process is microbial inoculation. The inclusion of microorganisms could improve the composting process by speeding up the decomposition of organic matter, mineralization, and the activities of microbial enzymes, as well as the quality of the finished products. This review will give a brief idea about the composting process, quality of compost and the most recent strategies for enhancing the composting process mainly with the help of microbes.

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1. INTRODUCTION

The rising demand for diverse agro-industrial-based products is indirectly influenced by the growing human population. The current Gross Domestic Product (GDP) contribution of the agriculture sector to the global economy for the year 2019 was 4% (or USD 87.7 billion) [1]. It is evident that the yield of the products harvested and the production of agro industrial crops are rising annually to fulfil market demand. Consequently, the increased output of agro - industrial goods will further enhance the production of trash and leftovers. The diverse residues related to agriculture and related activities is primarily generated by agro-industry. Crop residues are also a substantial but underutilised source of renewable biomass in agriculture, as they are produced in huge amounts. In India, the available crop residues are estimated to be around 620 million tonnes [2]. Half of the agro-residues thus generated are used as packing material, fuel, roofing material, and animal feed. The other half is burned in the field as waste. A cheap and convenient way to get rid of extra residues is to burn them in the field. This approach contributes to air pollution, causes soil erosion, and reduces the effectiveness of herbicides used in soil applications, such as isoproturon [3]. Additionally, it increases respiratory issues and increases the occurrence of fog, even in remote cities (Lalchandani, 2012). Three crops rice, wheat, and oilseed - produce around 50% of the total residues produced. These residues typically comprise 0.5% N, 0.2% P_2O_5, and 1.5% K_2O. The remaining residue has a nutrient potential of 6.5 million tonnes of NPK annually, or 30% of India's total NPK consumption. Therefore, recycling these wastes is not only necessary for the environmental sustainability, but it is also required for economic sustainability in a nation like ours. Composting is regarded as the most sustainable waste management strategy for turning agricultural and industrial waste and crop residues into useful byproducts [4]. Composting of agricultural residues by the action of lignocellulolytic microbes recycles lignocellulosic waste with great economic efficiency. Composting is termed as method of treating organic wastes by aerobic microorganisms and it comprises of three main stages: the mesophilic and thermophilic stages, and cooling (the compost stabilisation stage) [5]. Composting is the biological stabilisation and breakdown of an organic substrate under circumstances that allow the organism to generate heat, which results in the creation of a thermophilic temperature. As the mesophilic population grows during the composting process, the temperature of the heaps rises as a result of the consumption of simple nutrients at first [6]. “In the second stage, thermophilic microbes multiply. The finished product is reliable, clean, devoid of plant seeds, and suitable for use on land. The primary components of agro-industrial waste are complex lignocellulosic substances such cellulose, hemicellulose, and lignin. Despite the fact that it is an appropriate approach for treating agricultural residues. The difficulty of decomposing resistant compounds like cellulose, hemicellulose, and lignin is one of the most frequent difficulties for the composting of this type of waste. To enhance the composting process and produce high-quality end products, a variety of composting techniques had been put forth by researchers. This entails monitoring and managing crucial variables including the C/N ratio, moisture, and aeration to provide the ideal conditions for the composting process. Before the composting process, previous models employed pre-treatment techniques such hydrothermal and chemical treatments of the raw materials, primarily to break the lignin structure and remove other resistant components” [7]. “These pre-treatment techniques, however, are not practicable, mainly because of the chemical inputs and substantial energy required. Therefore, finding a safe, long-lasting, and economical treatment strategy is inevitably needed. Supplementation of microbial inoculant is currently seen as an appealing solution and there has been growing interest in studies microbial inoculant supplements in the compost heap as a means to improve productivity and end-product quality of the composting process” [8]. In light of the effectiveness of microbial inoculation for lignocellulose composting, this review sought to evaluate the state of the most recent developments and the understanding of compost supplementation with microorganisms and their roles in the biotransformation of organic materials during the composting process of agro-industrial waste. This review article focus on the process of composting, microbial inoculations involved in composting, benefits of compost and future aspects.

2. COMPOSTING FOR CROP RESIDUES AND AGRO-INDUSTRIAL WASTE

Composting is an aerobic, self-heating process of decomposing organic matter that is carried out in regulated conditions with the help of microbes to generate useful, stable, and humus-rich products useful for the soil and crop production. Additionally, composting is a better way to dispose waste than using a landfill or burning it. Composting technology has been included into the waste management systems of many agriculture-based sectors as a cost-effective and safe procedure. Costs associated with waste treatment are decreased by using this technology to turn organic waste into useful byproducts of decomposition. Organic wastes including paddy straw, sugarcane waste, and other agricultural wastes have been disposed by the process of composting. The efficiency of the various phases of composting is influenced by a number of factors, such as aeration, temperature, the amount of moisture in the compost, pH, the method of composting, and the nature of the mixture to be composted. However, the type of microorganisms involved and their activity are of utmost significance. Agricultural residues are mostly made up of polyphenolic components, complex proteins, and carbohydrates [9].

2.1 Quality Characteristics of Compost

The main characteristics of compost are as follows: [10]

- Appearance , colour and moisture content of compost
- Carbon to nitrogen ratio (C:N),
- Level of stability,
- Odour,
- Proportions of pathogenic microbes and heavy metals,
- Nutrient Content in the compost
- Size of the compost particles,
- Concentration of micronutrients
- and salt content.

3. EFFECT OF COMPOST ON SOIL'S PHYSICO-CHEMICAL AND BIOLOGICAL PROPERTIES

Applying compost to soil enhances its biological, chemical, and physical characteristics, as well as replenishing its organic matter and carbon reserves. Compost enhances the soil's pH, organic carbon and nitrogen content, cation exchange capacity, and water holding capacity while minimizing the probability of runoff and erosion and the soil's permanent wilting point [11]. Lou et al. [12] stated that "using mature composts made from used mushroom substrate raised the soil's nitrogen content from 157.35 mg N $kg^{-1}$to 400 mg N kg^{-1} after 42 days of incubation in comparison to control. On the other hand, compost application also boosted onion shoot numbers, shoot girth, and shoot length in addition to enhancing exchangeable sodium, potassium, calcium, magnesium, iron, and copper" [13].

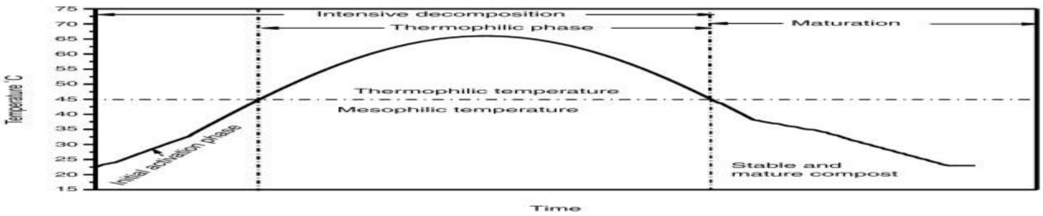

Fig. 1. Different stages of composting

Table 1. Optimum compost characteristics

Major parameters	Optimum quantitative characteristics
C : N ratio	20-40
Water Content	40-60
pH	5.0-8.0
Amount of fillers	More than 15 vol %
Content of organic matter	Not less than 40–60%
Composting temperature at thermophilic stage	Minimum 55–60°C
Amount of dry residue	35–45%
Ash content	15-25 %

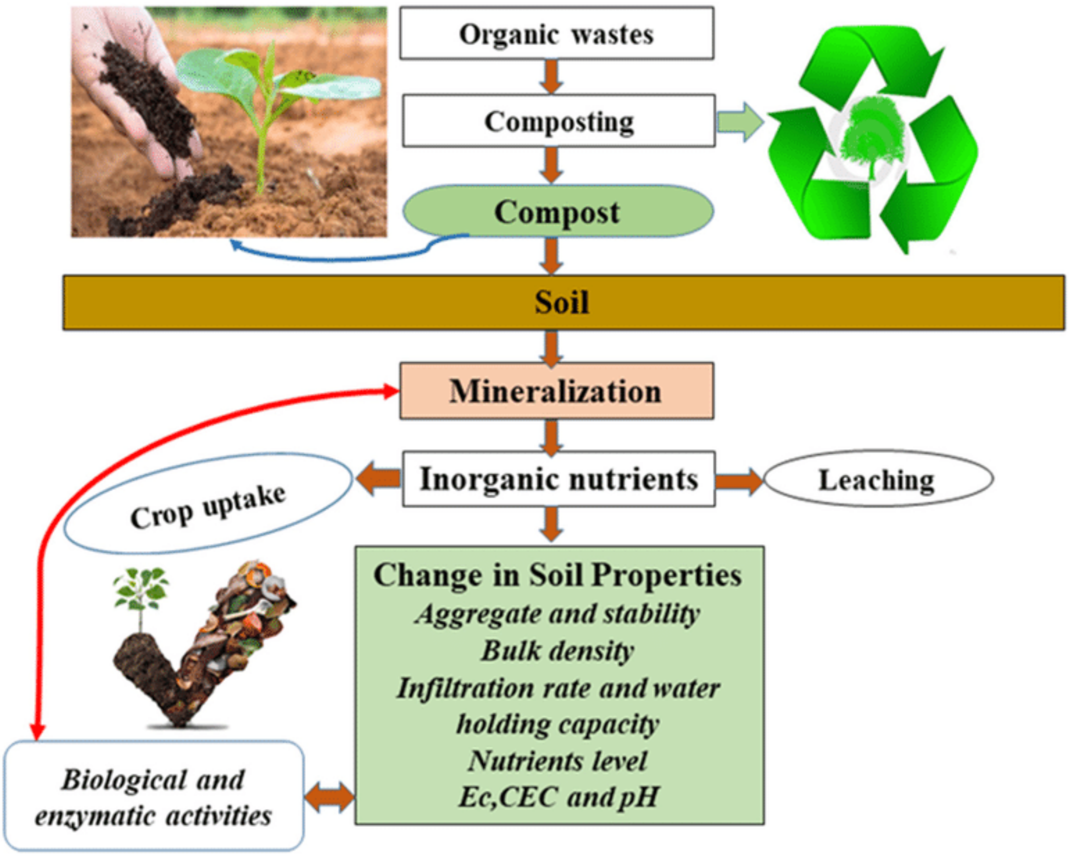

Fig. 2. Influence of compost on soil properties

Compost application improves soil biological fertility by promoting the growth of beneficial bacteria as well as suppressing soil-borne diseases. Plant pathogens that are present in soil can significantly reduce crop production. Although the precise mechanisms of disease suppression are unknown, they may involve the production of antibiotics by beneficial microorganisms found in compost, the occurrence of damaging or activating volatile compounds in compost, the stimulation of disease-resistant genes in plants by microorganisms (induced systemic resistance), enhanced plant nutrition and vigour that enhances disease resistance. In addition, harmful microorganisms that may be present in agro-industrial waste can be eliminated during the composting process, ensuring the compost's safety before it is applied to agriculture. Estrada-Bonilla et al. [14] stated that at the beginning of the composting process, bacteria from the order Xanthomonadales- also known as plant pathogenic bacteria—were found. However, their numbers decreased as a result of the composting process because the pathogen's growth was inhibited by the high temperature (>55 C) during the thermophilic phase. Research has shown that microbe-added composts have the ability to act as biocontrol agents with superior fungicidal activity, demonstrating the importance of compost as a nutrient source as well as a carrier for bioagents [15,16]. “Although successful biological control by compost has been less common in the field, several researchers have demonstrated the suppressive impact of compost on diseases such damping off, root rots, and wilts caused by *Fusarium*, *Pythium*, *Phytophthora*, *Verticillium*, and *Rhizoctonia”* [17]. At the time, chemical pesticides, herbicides, and fertilisers are heavily used in intensive agriculture methods [18]. “Despite the fact that chemical fertilisers can increase crop yield, their production and use have a number of negative effects on the agroecosystem, including soil degradation, loss of crop genetic diversity, reduction in soil microbial diversity, depletion of groundwater resources, and air pollution” [19]. Zhao et al. [20] reported that “using a combination of organic pig manure compost, inorganic compound fertilizer, with less chemical fertiliser was found to considerably boost wheat and rice yields as compared to the unfertilized control. The outcomes also demonstrated that this fertilizer regime enhanced soil nutrients, microbial biomass, enzymatic activities, and soil nitrogen transformation processes at all times when sampling was done. This demonstrated that the use of organic-inorganic compound fertiliser decreased the need for chemical fertilizer, maintaining the long-term productivity and sustainability of agro ecosystems. When such bioaugmented, nutrient-enriched compost is applied to soil, soil fertility is significantly improved, which improves the soil's overall chemical and biological activity. In comparison to application of simply chemical fertilisers, using a mixed fertiliser that includes chemical fertilisers, compost, and clinoptilolite zeolite has been shown to boost maize grain yield" [21]. "Similar research by Herecha et al. [22], revealed that utilising pro-mix in combination with 10% coffee pulp compost significantly increased seedling height, aerial biomass, and the number of nodes per plant in comparison to pro-mix medium alone, highlighting the significant advantages of using compost as an additional plant growth supplement. An economically appealing technique for removing organic contaminants such xenobiotics, petroleum products, polycyclic aromatic hydrocarbons (PAHs), etc. is bioremediation using co-composting. In addition to agriculture, bioaugmented compost is gradually becoming a new resource for bioremediation of soil contaminated with organic pollutants and heavy metals. When applied to heavy metal-contaminated soils, compost limits the bioavailability of metals because it contains iron oxide, humic substance, and organic materials. Moreover, stabilised organic matter binds with metals to form complexes, which limits the mobility of the metals and their availability to plants for absorption" [23]. Furthermore, microorganisms like bacteria and fungi which are involved in composting have the capacity to chelate metal ions via carboxyl, hydroxyl, or other active functional groups on cell (even dead cell) wall surfaces and to collect metal ions in their cells by intracellular absorption.

4. STRATEGIES FOR ENHANCING COMPOSTING PROCESS

"It typically takes 180 days to produce good, mature compost when lignocellulose-rich agricultural residues like paddy straw are composted. The enzymatic and microbiological access to the cellulose in paddy straw is constrained by the high lignin level. Microorganisms that break down cellulose speed up the biodegradation of agricultural wastes like straw, leaves, trash, etc., and these cultures have been employed to decompose plant residues but the composting process still takes too long. Agro-industrial waste can be difficult and time-consuming to compost conventionally. Composting is influenced by a wide range of parameters, including raw materials, timing, environment etc. Previous research shown that adding inoculum had little impact on how rapidly wheat straw, farm waste, and grape pulp decomposed into organic matter" [24]. "Because of competition between the inoculant and native microorganisms, the type of inoculation and the time of the inoculation the inoculation does not always perform well. As a result, researchers have experimented with a variety of methods to enhance the composting process by the inclusion of inoculums. Adding microbial inoculum at different phases of the composting process is one of the promising strategies. The microbial inoculum can be added in first stage, second stage, or multiple stages of the composting process, and when the inoculum was added at various stages of the composting process, a substantial impact on physicochemical parameters was seen" [25]. For instance, a study by Zeng et al. [26] found that "the inclusion of Phanerochaete chrysosporium during the second phase of the agricultural waste (rice straw + bran + vegetable) composting process promotes a significant change in compost maturity as compared to the inoculation during the first phase. Composting of rice straws" [27], maize straws (Zhao et al. 2016), and citrus peels [28] revealed significantly increased lignocellulose degradation after bacterial inoculation, which decreased the C/N ratio and composting time. Fan et al. (2017) observed that microbial inoculation had a nearly 100% positive impact on temperature, enzyme activity, "microbial population, C/N ratio, humification, and more than 50% on organic matter degradation, germination index (GI), and on N, P, and K content during the composting of lignocellulosic waste. The research further showed, that the inclusion of microbes makes municipal solid waste composting less successful. This is so that existing or native bacteria can easily breakdown degradable organic material found in municipal solid waste. It is important to keep in mind that monitoring microbial inoculants is necessary to guarantee their survival and their influence on native microbes when compared with the microbial succession with the uninoculated composting process. This can be accomplished via culture-based techniques or culture-independent techniques, such as high-throughput 16S rRNA gene sequencing and polymerase chain reaction-denaturing gradient gel electrophoresis (PCR-DGGE)" [29].

As previously noted, various experts have found that the inoculation of effective microorganisms has numerous beneficial effects on the composting process. The microbial inoculum can include single culture, mixed culture, or mature compost. Several effective microbial cultures, a common compost inoculum is a mixture of non-dominant and dominant microorganisms. It has been claimed that the best way to solve the issue of competing with native bacteria of the composting pile is to add a microbial consortium. Re-inoculating isolated microorganisms from the composting process itself is another approach that could improve composting performance. It has been recommended that microbial inoculation with particular bacteria and/or enzyme-producing microbes could improve the composting process by ensuring the right microbes are added in the piles at the proper temperatures, oxygen levels, and moisture regimes at the proper times. This was demonstrated in a research by Zhou *et al.,* "the inoculation of thermophilic *Thermoactinomyces sp.* at the initial stage, followed by ligninolytic *Coprinus cinarea* and *Coprinus comatus* after the thermophilic stage, and finally cellulolytic *Trichoderma harzanium* and *Rhizopus oryzae* at the maturing stage, increased the temperature and the rate of cellulose and lignin degradation of dairy manure-rice straw composting". More significantly, each of these inoculants were separated from the compost of rice straw and dairy manure. On the other hand, it should be noted that some research suggests there are major disadvantages to using commercially effective microorganisms in the composting process. "This results from irregularities in the EM formation during the composting process. T the elements that creates an environment that is less suitable for the inoculant to develop, live, and function properly throughout the composting process are the characteristics of raw material's and the climate" [30,31]. Van Vliet et al. [32] found that "adding EM to slurry manure to composting to prevent nitrogen loss did not affect the quality of the compost because there was no discernible difference in the ratio of mineral N to organic N between the treatment and control. This was done to prevent nitrogen loss. The microbial profiles of the EM-manure composting and the EM solution were compared, and the results revealed that many of the bacteria in the EM solution were absent from the manure to which the EM was added" [33]. Therefore, obtaining a stable inoculum is essential for improving both the composting process and the quality of the end product. This problem can be resolved by reinoculating the compost isolates as previously described.

5. MICROBIAL INOCULATION AS A MEANS TO IMPROVE COMPOSTING PROCESS

"Despite the distinct and significant roles that fungus, bacteria, and actinomycetes play during composting, mixed cultures of microorganisms accelerate the decomposition of lignocellulose because of their synergistic activity and consumption of intermediate degradation products" [34]. According to earlier research, adding microbes to the composting process boosted mineralization [35], speed up OPEFB's composting time from 64 to 50 days, and increased the total nitrogen, phosphorous, and potassium content of rice straw and cattle dung to raise compost maturity [36]. A group of four fungus has been identified at IARI in New Delhi based on their ability to produce lignocellulolytic enzymes [37]. Paddy straw was composted in perforated pits using a combination of four hypercellulolytic fungal cultures: *Aspergillus nidulans*, *Trichoderma viride*, *Phanerochaete chrysosporium*, and *Aspergillus awamori*. *Aeromonas caviae* sp. SD3, *Shinella sp*. XM2, *Rhizobium sp.* S8, *Corynebacterium pseudotuberculosis sp.* SD1, and *Streptomyces clavuligerus sp*. XM, which were screened from rice straw compost, were re-inoculated into the composting pile. This accelerated the degradation of organic matter and coarse fibre content by 7.58% and 8.82%, respectively [38]. Additionally, Yang et al. [39] reported that a microbial inoculum containing the cellulose- and lignin-degrading Ralstonia sp. (LT703298), Penicillium sp. (LT703297), Penicillium aurantiogriseum (LT703295), and Acremonium alternatum (LT703296) bacteria was inoculated and enhanced the enzymatic activity of polyphenol oxidase (0.3 to 28.4%), urease (2.3 to 71.4%), and cellulase (15.0 to 19.8%), which shortened the composting time and improved the maturation rate in pig dung in comparison to the control treatment (uninoculated).

Henry et al. [40] observed that adding effective microorganisms (EM) to the composting of pine waste, chicken manure and rice bran could increase the population of thermophiles that will further enhance composting in comparison to control. Within two months of composting, the addition of chicken droppings and rock phosphate (1%) produced N-enriched phosphor compost. *A. nidulans*, *Scytalidium thermophilum*, and *Humicola sp*. formed a thermophilic fungal consortium that was extremely successful in degrading a mixture of soybean waste and paddy straw during the summertime [41]. Wang et al. [28] revealed that the addition of a bacterial consortia inoculant increased the concentration of the *Sphingobacterium*, *Bacillus* and *Saccharomonaspora* genus, which accelerated the decomposition of pectin and cellulose in citrus peel, bran, and lime during composting. This in turn decreased the C/N, organic matter, and moisture. Likewise, adding phosphate-solubilizing bacteria to sugarcane waste composting increased bacterial growth, particularly of the order Lactobacillales, and caused a rise in temperature in the initial phase, which aided in the breakdown of the lignocellulosic content and, thus, an enriched phosphorus content at the end [14].

Wan et al. [42] concluded that the inclusion of a microbial cocktail inoculum composed of *Bacillus licheniformis, Bacillus amyloliquefaciens, Bacillus megaterium, Bacillus pumilus, Geobacillus pallidus, Ureibacillus thermosphaericus,* and *Paracoccus denitrificans*, which were isolated and cultured from chicken manure and maize straw compost, improved the thermophilic phase of composting with maximum temperature reaching 68 ◦C when compared to control treatment with only 60.8 ◦C as the maximum temperature. As a result, the germination index rises as high temperatures lessen the influence of phytotoxicity, resulting in a better compost maturity level [43]. Earlier, Zhang et al. [44] 2016 found that inoculation of enhanced ammonia-oxidizing bacteria efficiently decreased emission of ammonia by 53% of total ammonia as compared to uninoculated compost by stimulating transformation of ammonia into nitrate. Pig dung and corn stalk composting took two more days to reach the thermophilic stage after being inoculated with a combination of bacteria (*Acinetobacter pittii*, *Bacillus subtilis* sub sp. Stercoris, and *Bacillus altitudinis*) [45]. At the completion of the composting process, the inoculation of these bacteria enhanced the total phosphorus and showed no plant toxicity. Their research revealed that the prolonged thermophilic period decreased the amount of functional genes associated with human disease, which was caused by the eradication of a significant number of harmful bacteria.

Fungal inoculation has so far proven to be an efficient way to speed up the composting process. White-rot fungus (*Phanerochaete chrysosporium*), which produces the extracellular enzyme system composed of manganese peroxidase, lignin peroxidase, and laccases for lignocellulose breakdown, is one of the important and frequently utilised fungi in composting [46]. Huang et al. [47] revealed that inoculating with *Phanerochaete chrysosporium* significantly decreased the toxic hazards in the composting of lead (Pb)-contaminated soil, rice straw, bran and vegetables. *Phanerochaete chrysosporium* also displayed positive effects on the bacterial community composition using DGGE profile analysis, which helped to lower the concentration of harmful Pb^{2+} ions. According to a study by Chen et al. [48] composting of agricultural waste and river silt without the addition of *Phanerochaete chrysosporium* lowered the bioavailability of heavy metals for cadmium, plumbum, and zinc, respectively. This is because *Phanerochaete chrysosporium* encourages the passivation of heavy metals by chelating them with the help of organic humus. Additionally, it was discovered that *Phanerochaete chrysosporium* inoculation caused copper to passivate more quickly than other heavy metals throughout the composting process. According to Xie et al. [49], the inoculation of a consortium of cold-adapted microorganisms made up of the strains *Pseudomonas fragi* (KY283110), *Pseudomonas simiae* (KY283111), *Clostridium vincentii* (KY283112), and *Pseudomonas jessenii* (KY283113) and *Iodobacter fluviatilis* (KY283114) greatly accelerated the disintegration of organic matter and enhanced the temperature at low ambient temperatures (10 C), which helped to begin composting in winter or cold or cold climates. Cao et al. [50] reported that, adding microbial agents which comprised of yeasts, actinomycetes lactic acid bacteria and photosynthetic bacteria, to the composting process accelerated the decline of total ARGs by altering the differences in ARG profiles and the probable hosts of ARGs (bacterial community), which further affects the removal of ARGs. Similar results were obtained when 0.5% (w/w) of Bacillus subtilis was added to a mixture of bovine manure and wheat stalks during composting, which resulted in a reduction in the relative abundances of ARGs, mobile genetic elements, and human pathogenic bacteria [51]. Similar to this, the Directorate of Mushroom Research in Solan employs a group of thermophilic microorganisms (*Scytalidium thermophilum*, *Humicola insolens*, and *Sporotrichum thermophilum*) to produce compost at elevated temperatures in tunnels that is pathogen-free and gets ready within just ten days.

6. BIO-COMPOSITES

Biocomposite is a material composed of two or more distinct constituent materials (one being naturally derived) which are combined to yield a new material with improved performance over individual constituent materials. The material such as fibers which are used in bio-composites are produced from agricultural products and byproducts, which are subsequently intermixed with different polymer-based matrices. These are biodegradable and renewable polymer matrices which are mixed with lignocellulosic fibers. The natural fibers are mostly used as reinforcements but also can be used as matrix material [52-54]. Bio-composites fall under the category of polymer matrix composites. Polymer matrix composites are made up of natural (PLA, PHA, PCL) or synthetic matrix materials (thermoplastic, thermosetting plastic), with one or more reinforcements such as carbon fibers, glass fibers or natural fibers in the case of bio-composites. Cellulose fibers are organic and are produced from biomass and associated derivatives of agricultural products Cellulose is currently considered one of the most studied and used polymers, followed by approximately 40–60% of plant matter consists of cellulose, in addition to hemicellulose, lignin, and pectin. Verma et al. [55] revealed that chicken feathers in form of reinforcing fibers when taken in different weight percentage enhances the tensile strength, flexural strength and overall impact strength enhancement. Verma and Singh, [56] revealed that human hair treated with potassium hydroxide and curing of polymer enhances the bonding properties of composites. Thus, bio-composites are a novel tool to reduce environmental degradation [57,58].

7. FUTURE PROSPECTS

The composting process has been extensively studied throughout the world, but there are still many scientific and technological concerns that need to be resolved in order to increase the effectiveness of the procedure and the quality of the final product. Main research directions include enhancing the decomposition process, providing extra nutrients, examining microbial populations, and enhancing the effectiveness of composting techniques. Compost use in various areas of agriculture has been revolutionised, and it is now a crucial component of crop production, crop protection, and natural resource management. New techniques to improve composting include shortening the generation time, incorporating animal waste and faeces, organic and inorganic compounds, and consortia of efficient microorganisms. Although much research has been done on the microbiology of composting, there is still a lack of knowledge regarding the diversity of microorganisms and their precise functions at different phases of composting. Research on unculturable microorganisms and their activity throughout the composting processes is urgently needed, and it should make use of advanced methods like denaturing gradient gel electrophoresis (DGGE) and other culture independent techniques. There are still a number of crucial knowledge gaps regarding the improvement of the composting process by inoculation. For example, a limited amount of study is available regarding the generation of compost from agro-industrial waste, mainly at the commercial or semi-industrial scale. In order to validate the repeatability and benefits observed in small-scale studies, more research on microbial inoculations at the semi-industrial or commercial size is necessary for all composting techniques, including the in-vessel system and the aerated static pile. Farmers must be made aware of various composting technologies by extension specialists and KVKs. Agro-wastes can be used as a resource for the manufacture of animal feed, bio-fuel, and enzymes in addition to composting, which could result in additional profit from the bioconversion process.

8. CONCLUSION

Various beneficial outcomes result from the addition of numerous efficient microorganisms to the composting process. The composting of agricultural waste can be enhanced by using a variety of inoculation techniques, including the addition of inoculants at different stages and the inoculation of a single or mixed microbial culture. Composting is one of the most practical solutions, although research and development are clearly needed to improve the design and operation of biotechnological applications that improve soil conditions. To fully comprehend the mechanisms of microbial inoculation's effects on composting, additional research is required. At both the pilot scale and the industrial scales, it is also vital to look at the interactions between the composting pile, microbial inoculum, the native microbial community, and the composting processes. Based on the type of agricultural waste material, this review could be a useful source for choosing appropriate and effective microbial inoculants for the enhancement of the composting process.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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