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Fungi: The Next Generation of Biofertilizers

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Abstract

Understanding the negative impacts of using chemical fertilizers on living organisms and the environment, in general, has encouraged finding natural alternatives. Hence, biofertilizers are applied through soil or seed and are prepared from promising microbial strains (living or dormant cells) that help economically important plants in taking nutrients by interacting with their rhizosphere. Fungi are famous contributors in this field due to their ability to live in different ranges of environmental habitats and carry out processes such as nutrient cycling and decomposition of organic matter. However, many types of interactions were reported between fungi and other organisms as ants or microorganisms as bacteria. In this review, we focus on understanding what biofertilizers are, how they act and what type of interactions are noticed among them. Moreover, the classification of biofertilizers and some of their carriers are highlighted. Furthermore, we introduced examples of some fungal genera that are used as promising biofertilizers.

Keywords: Biofertilizers; Fungi; Bacteria; Phosphorus solubilizing; Nitrogen fixation

Introduction

With the rapidly increasing population, the environment is getting disturbed due to urbanization and industrialization. It is difficult to feed the entire population of the world which is significantly increasing day by day (Bhargava et al., 2019a). The natural systems have been modified by humans due to the production of food globally. The use of fertilizers has made it possible to meet the demands of the world's food supply. But due to this practice of excessive utilization of fertilizers, the environment has been affected to a great extent. It has led to the contamination of groundwater, affecting the quality of soil and biodiversity (Kumar et al., 2020b). Further, plants face certain environmental stresses, both biotic and abiotic, which have a negative impact on the yield and growth of crops. Abiotic stresses which include temperature of environment, salinity, pH of the soil, etc., have always affected agriculture (Bhargava et al., 2019b). Therefore, instead of utilizing chemical fertilizers, an alternative method to deal with these situations is to elevate the use of biofertilizers (Kumar et al., 2020a). Biofertilizers need to be preferred over chemical fertilizers as they are cost-effective, secrete growth hormones, uplift crop yield, improve nitrogen fixation, and do not cause harm to the environment (Mahanty, 2017). Therefore, the use of beneficial microbes as biofertilizers has become an increasing area of research in agriculture and life sciences owing to the role they play in food security and sustainable agro-crop production. Their interactions and activities lead to increases in crop yield, the earth's geochemical, stability, climatic, and biogeochemical cycles (Hansel et al., 2008). This review focuses on fungi biofertilizers for the next generation.

Biofertilizer

In the rhizosphere, there is a large number of microorganisms present in the soil. There is an interaction between plants and microorganisms in the rhizosphere. Some of these microorganisms have a functional relationship with plants. This relationship is beneficial for the plants in different ways such as enhancing their growth and providing resistance to environmental stress which include contamination of heavy metal, and deficiency of nutrient and water (Sharma et al., 2018). Therefore, biofertilizers are those preparations carrying living or latent cells of potent microbial strains that help economically important plants in taking nutrients through interacting in the rhizosphere.



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Biofertilizers are a combination of organic matter and useful microorganisms. Xiong (2017) reported that organic matter acts as a niche for microorganisms and also helps in recycling. The important nutritional elements became available with the help of these microorganisms via various biological mechanisms. Now, biofertilizers are an important part of the system which supplies nutrients and have a crucial role to play in improving the yield of crops (Singh and Vats, 2019). They are gaining popularity in different parts of the world as they are found to protect the roots of the plant from pathogens present in the soil along with the enhancement in the fertility of the soil. The microbiota of the bulk soil is modified by the addition of biofertilizers (Tandon and Vats, 2016). For the management of integrated nutrients, using biofertilizers is considered one of the main components, due to being a cheap and renewable source of nutrients for the plants. Several microbial species and their association with crop plants are studied for their ability to be used as biofertilizers.

Fungal Biofertilizers

Mycological studies have shown that fungi live in a wide range of environmental habitats and carry out processes such as nutrient cycling and decomposition of organic matter. Recently, applying fungi to arable land in order to improve the quality of the soil has attracted serious attention due to its promising results (Bagyaraj and Ashwin 2017). In this process, fungi colonize the plant roots region (rhizosphere) in order to promote growth. This phenomenon usually increases the efficient distribution of essential nutrients to the target crops while also maintaining soil inhabitants, owing to their ability to adopt various forms in response to unfavourable conditions. Kumar et al. (2018) in their work reported that these fungi could be used in seeds, applied on plant surfaces or in the soil to stimulate growth. They have also been implicated in continuously helping in the release of nutrients through their metabolism (Malusa et al., 2012). Some of the common microorganisms usually used as biofertilizers are nitrogen-fixing agents (Odoh et al., 2019), plant growth-promoting rhizobacteria (Yadav et al., 2018a), potassium solubilizers (Kour et al., 2020), phosphorus solubilizers (Yadav et al., 2017a), cyanobacteria and endomycorrhizal and ectomycorrhizal fungi (Itelima et al., 2018). Basically, these microorganisms have the ability to produce an assortment of potent extracellular enzymes that can break different organic components (Frąc et al., 2018).

Fungal–Fungal Interactions

In this process, fungi make an obligate symbiotic relationship with leaf-cutting ants. Following a series of systematic steps, plant leaves are cut and transported to the nest where they are cleaned up, processed, and utilized as substrate. At the same time, fungi utilize leaves by converting its biomass into nutrients for the worker ant population and their larvae. This is however achievable due to the activities of fungi living in the underground chambers (Van Bael et al., 2011). Moreover, this process undermines the behaviour of leaf-cutter ants including plant fungal endophytes. Similarly, they also synthesize organic compounds with antimicrobial and insect-repellent characteristics (Borges et al., 2009). These compounds thus provide an avenue for microbial competition within the community, while altering the chemical and adaptive defense system (Pettit, 2009). Additionally, Van Bael et al. (2011) have reported the associative roles of some fungal endophytes on leaves and how they enhanced lignin deposition in plants' cell walls.

Bacterial–Fungal Interactions

Ecological studies have revealed that bacteria and fungi co-habit through their assemblage into complex and dynamic co-evolving groups. Fungal and bacterial communities are found in all ecosystems (Scherlach et al., 2013), and the interactions between these microbes play a huge role as they are considered vital players in driving activities such as biochemical cycles and contributing in a significant way to plant and animal pathogens (Deveau et al., 2018). These agents have been utilized for the production of food and its processing (Odoh et al., 2017), pharmaceuticals and antibiotics synthesis, biotechnology and production of metabolites (Frey-Klett et al., 2011). Also, in characterizing the bacterial fungal interaction, understanding microbiomes using molecular

tools, chemical and microbial ecology, genomics, and biophysics are essential (Bergelson et al., 2019).

Arbuscular mycorrhizal fungi and bacteria (plant growth promoting rhizobacteria) association have been reported to promote crop growth (Pathak et al., 2017). As reported by Philippot et al. (2013), *Bacillus* sp., *Pseudomonas* sp. and Arbuscular mycorrhizal fungi interaction proffers strong viability and causes important enhancement in field study when applied singly or in the combined application (Pathak et al., 2017). Although this association has a positive influence on crop yield, it also enhances soil nutritional status and soil microbial biodata.

Biofertilizers Classification

Biofertilizers are composed of diverse microorganisms that when administered to plants, and seeds stimulate their growth. Both nitrogen fixation and phosphorus solubilization are important biological processes (Singh, 2016). Biofertilizers also prevent the plants from getting infected by several diseases, e.g., *Fusarium* wilt disease (Li, 2017). Figure 1 shows the classification of biofertilizers on the basis of function and nature.

Phosphorus is an important macronutrient. Due to reduced levels of soluble phosphate in the soil, the plant is not able to grow properly. To overcome this issue, P-fertilizers were commonly made into use. In spite of this, a very small quantity of phosphorus is used up by plants and most of it is precipitated in the form of complexes of aluminium, iron, and calcium. Phosphorus uptake from soil by plants is not easy. However, some microorganisms are capable of solubilizing phosphorus acting as biofertilizers. They convert the phosphorus which is insoluble into soluble form which is readily taken up by the plants. This approach of using phosphorous biofertilizers is responsible for improving the yield of agriculture in several countries (Wang, 2015). Nitrogen is one of the vital nutrients utilized by plants. Nitrogen fertilizers are used to obtain the necessary nitrogen required for development and growth of plants. Such fertilizers have bad impacts on the environment when applied in excess amounts. Therefore, biofertilizers are used as safer alternatives in order to satisfy plants' needs (Vats et al., 2019). Also, plants need help in order to take atmospheric nitrogen. Hence, it is first converted into ammonia by the process of nitrogen fixation and then the assimilation takes place. The nitrogen-fixing microorganisms fix nitrogen with the help of nitrogenase enzymes. These microorganisms are present in biofertilizers (Mahanty, 2017). They also assist in water and mineral absorption (Vats et al. 2012).

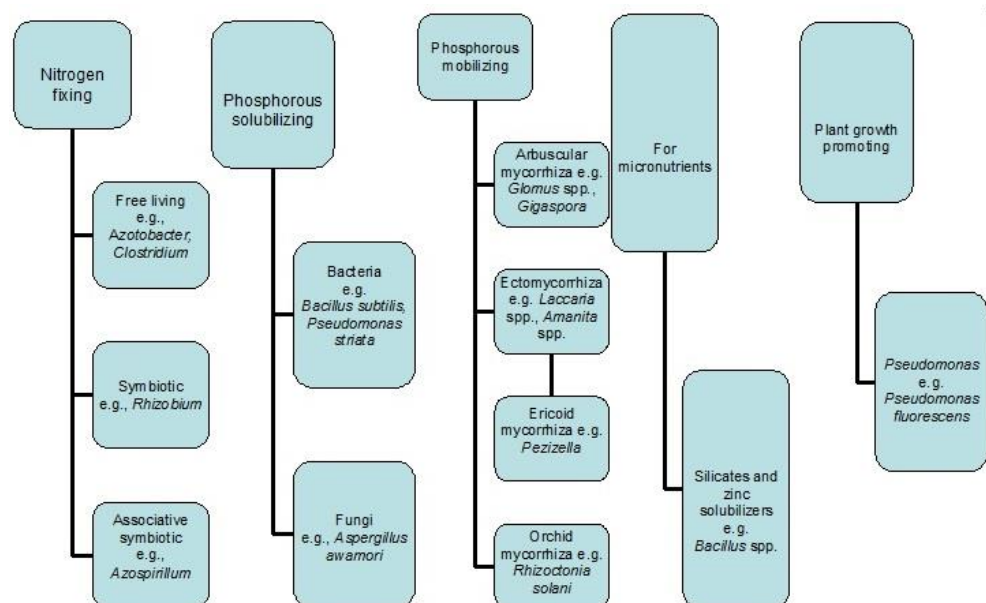


Figure (1): Classification of biofertilizers on the basis of function and nature

Carriers of the Biofertilizers

Biofertilizers are prepared using a carrier composed of microorganisms (Wang, 2015). It is considered as a transporter of biofertilizers from the manufacturing unit to the field. There are different carriers for different biofertilizers (Mahanty, 2017). Peat is applied as a biofertilizer carrier in various countries. A promising carrier should have some specific properties such as being eco-friendly, or in the form of granules or powder, able to absorb moisture, helping the microbes to grow and survive, cost-effective, and able to easily discharge the useful microorganisms into the soil.

Perlite is also an eco-friendly biofertilizer carrier used which is composed of aluminium silicate and some amount of water. It is also porous and lightweight. In order to store the biofertilizer carrier for a long period of time, its sterilizations are crucial. On the other hand, one of the methods to sterilize the carrier material is through gamma irradiation. This technique is accessible and causes limited losses during storage. Biofertilizers on carriers are preferred over free-cell as carriers provide protection to the microorganisms from environmental stress. Thereby, providing shelter to the microbes.

Fungal Biofertilizers and Agriculture

Biofertilizers are composed mainly of microbes such as fungi, algae, and/or bacteria with the ability of fixing nitrogen, adding nutrients to soil and solubilizing minerals to fulfil plant needs. They are environmentally friendly, cost-effective, and renewable sources of plant nutrients that have gained acceptance over chemical fertilizers (Kour et al., 2020). These bio-based materials play an important role in maintaining soil fertility, nutritional enrichment, and sustenance of healthy soil for generations (Mishra et al., 2015).

Mycorrhizas are unique microbes that form mutual symbiotic relationships with plant roots. They interact with these plants and enhance the uptake of phosphorus (P), nitrogen (N), zinc (Zn), copper (Cu), iron (Fe), sulphur (S), and boron (B). Some of plants with mutualistic association with mycorrhiza species include herbs, shrubs, trees, xerophytes, epiphytes, and hydrophytes (Rai et al., 2013).

Fungi used as biofertilizers

***Trichoderma* spp.**

Trichoderma is a fungal genus commonly found in most habitats. They are predominantly found in root and soil ecosystems and are considered ubiquitous saprobes. Some *Trichoderma* strains interact with their plant's host, increasing their growth potential and imposing resistance against diseases and abiotic stresses (Rosa et al., 2012). *Trichoderma* spp. has been engineered over time to successfully support crops such as potatoes, corn, tomato, peanut, beans, cotton, and soybean (Sneha et al., 2018).

***Chaetomium* spp.**

Chaetomium species exist mainly in organic compost and soil. It is a promising fungicidal agent used frequently for protective and curative purposes. Ketomium is an important secondary metabolite that is formulated from both *Ch. Globosum* and *Ch. cupreum* and acts as plant growth stimulant (Jehangir et al., 2017). As a promising strategy, *Chaetomium* spp. can suppress bacterial and some other fungal growth through mycoparasitism, competition, and antibiosis (Marwah et al., 2007).

***Penicillium* spp.**

Penicillium spp. are phosphorus solubilizing agents. They act as biofertilizers by enriching compost and soil quality (Sharma et al., 2013). Some of the important species in this genus are *P. bilaji*, *P. italicum*, *P. simplicissimum*, *P. oxalicum*, *P. frequentans*, and *P. rubrum* (Yadav et al., 2018b). Also, Mishra et al. (2013), suggested that a combination of *Penicillium* and *Trichoderma* increases the development of wheat and soybean under nursery conditions. Elsewhere, *P. italicum* from the rhizosphere soil also has the ability to solubilize tricalcium phosphate (TCP) and promote efficient

soybean growth and production (Ram et al., 2015), while *Penicillium* spp. serves as phosphate solubilizer and general plant growth stimulator (Sumita et al., 2015).

***Aspergillus* spp.**

Aspergillus niger; this agent facilitates plant growth through root formation (bio-promoter). It improves soil quality and can be used to produce zinc solubilizing biofertilizers. Ambiphos is one of the promising biofertilizers made from *Aspergillus niger* as it secretes organic acids that help in converting insoluble phosphate into soluble form and make its uptake by plants much easier. On the other hand, the genera (*A. flavus*, *A. tubingensis*, *A. awamori*, *A. terreus*, *A. fumigates*, *A. niger*, and *A. melleus*) are able to solubilize inorganic phosphate through the production of citric acid, gluconic acid, glycolic acid, oxalic acids, and succinic acid. *Aspergillus fumigatus* which is most often isolated from compost has been reported to be potassium releasing fungus (Sharma et al., 2013).

***Gliocladium* spp.**

Gliocladium species are common saprophytes that exist mainly in soil. They are also parasites on different plant pathogens such as *Sporidesmium sclerotiorum* and *Fusarium* spp. *Gliocladium virens* has been used as a biological control agent against a wide range of soil-borne pathogens such as *Pythium* and *Rhizoctonia* under greenhouse and field conditions. It also produces antibiotic metabolites such as gliotoxin which has anti-bacterial, antifungal, anti-viral, and anti-tumor activities (Nissipaul et al., 2017).

Conclusion

Chemical fertilizers have been more popular in recent decades for use in agriculture, while biofertilizers are a more environmentally friendly option. Fungi are the most well-known among them. By preventing infections' growth and limiting some of their biological functions, fungi biofertilizers reduce the frequency of plant diseases. They create hormones and enzymes that promote plant growth in addition to enhancing the uptake of nutrients from the soil and creating bioactive substances. On the other hand, microorganisms as natural alternatives of harmful chemical biofertilizers have attracted serious attention. Fungi are promising contributors in this field with various types of interactions. Further studies are encouraged to understand the potential of these promising microorganisms in this field and their impact on plants' health.

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DEE, WAE and GMD conceived the concept, wrote and approved the manuscript.

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Competing interest

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Ethics approval

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