Chronicle of Bioresource Management 2020, 4(2):026-030

Chronicle of Bioresource Management
An International E-magazine

December, 2020 *Popular Article*

Biofertilizers: A Sustainable Approach to Enhance Rice Cultivation

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Citation: Ankireddypalli et al., 2020. Biofertilizers: A Sustainable Approach to Enhance Rice Cultivation. Chronicle of Bioresource Management 4(2), 026-030.

Data Availability Statement: Legal restrictions are imposed on the public sharing of raw data. However, authors have full right to transfer or share the data in raw form upon request subject to either meeting the conditions of the original consents and the original research study. Further, access of data needs to meet whether the user complies with the ethical and legal obligations as data controllers to allow for secondary use of the data outside of the original study.

Conflict of interests: The authors have declared that no conflict of interest exists.

Keywords:

Biofertilizers, sustainable agriculture, rice cultivation, nitrogen-fixing bacteria, phosphate solubilization, environmental sustainability

Article History

Article ID: CBM24a
Received on 05th August 2020
Received in revised form on 20th November 2020
Accepted in final form on 09th December 2020

Abstract

Rice is a staple food for nearly half of the global population, yet conventional farming practices rely heavily on chemical fertilizers, leading to soil degradation, water pollution, and environmental concerns. As the demand for sustainable agriculture grows, biofertilizers have emerged as an eco-friendly alternative, enhancing soil fertility and promoting plant growth through beneficial microorganisms. Biofertilizers, including nitrogen-fixing bacteria (e.g., *Rhizobium*, *Azospirillum*), phosphate-solubilizing microorganisms (e.g., *Pseudomonas*, *Aspergillus*), and plant growth-promoting rhizobacteria (PGPR), play a crucial role in nutrient availability and soil health. Their application in rice cultivation reduces dependency on synthetic fertilizers, improves crop resilience to environmental stress, and supports long-term agricultural productivity. Furthermore, biofertilizers contribute to global sustainability goals (SDGs), such as climate action (SDG 13) and food security (SDG 2), by reducing greenhouse gas emissions and enhancing yield stability. As concerns over chemical-based agriculture rise, biofertilizers present a promising solution for sustainable rice farming, ensuring environmental protection while maintaining food security for future generations.

1. Introduction

Rice is a staple food for approximately 3.5 billion people worldwide, accounting for about 19% of global dietary energy. With the global population projected to exceed 9 billion by 2050, food demand is expected to rise by 35% to 56%. Despite the high demand, current rice cultivation practices are heavily reliant on chemical fertilizers and pesticides to boost productivity, which presents significant long-term challenges. Intensive chemical use degrades soil health by depleting nutrients and impairing water retention, which results in environmental pollution, particularly water contamination. In contrast, biofertilizers enhance soil health and nutrient cycling, reducing the need for chemical fertilizers that contribute to greenhouse gas emissions (Timmusk et al., 2017). The high costs of these practices, along with their negative effects

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on biodiversity and soil fertility, pose a significant threat to the long-term sustainability of rice production. To address these challenges and meet global food demands, alternative strategies for crop nourishment are critical. One promising solution is biofertilizers-organic products containing beneficial microorganisms from plant roots and rhizosphere regions. These microorganisms can improve soil fertility, enhance plant growth, and promote a healthier, more sustainable agricultural ecosystem. Sustainable farming practices, especially the use of biofertilizers and organic fertilizers, present a promising way to boost crop yields while reducing the environmental impact of agriculture. Biofertilizers enhance soil health and nutrient cycling, decreasing the reliance on chemical fertilizers, which are linked to greenhouse gas emissions. This strategy supports SDG 13 by helping to combat climate change through environmentally friendly methods and contributes to SDG 2 by strengthening plant resilience to environmental stress, thereby improving food security.

2. Biofertilizers

Biofertilizers are substances that contain living microorganisms, which enhance soil fertility and promote plant growth by increasing the availability of nutrients. These microorganisms, which include bacteria, fungi, and algae, are used to naturally improve the health of plants and soil without the harmful effects of synthetic fertilizers. Biofertilizers can be applied in a variety of ways, including soil inoculation or as seed treatments, and are a sustainable and environmentally friendly alternative to traditional chemical fertilizers.

Biofertilizers are classified based on their specific functions and modes of action. The major types include nitrogen-fixing biofertilizers, phosphate-solubilizing biofertilizers, potassium-solubilizing biofertilizers, and plant growth-promoting rhizobacteria (PGPR) (Mahdi et al., 2010).

2.1. Nitrogen fixing biofertilizers

Nitrogen is a critical nutrient for plant growth, yet most plants cannot directly absorb atmospheric nitrogen. Nitrogen-fixing microorganisms, such as *Rhizobium*, *Azotobacter*, and *Azospirillum*, convert atmospheric nitrogen into forms that plants can use (Reed et al., 2011). These biofertilizers can supply up to 300–400 kg of nitrogen per hectare annually, resulting in increased crop yields of 10-50%.

• ***Rhizobium*** is particularly important for legumes, where it forms a symbiotic relationship, fixing nitrogen in specialized nodules on the plant roots. This nitrogen enriches the soil, benefiting future crops. Studies have shown that *Rhizobium* inoculation can increase rice yield by up to 22% under optimal conditions (Sammauria et al., 2020).

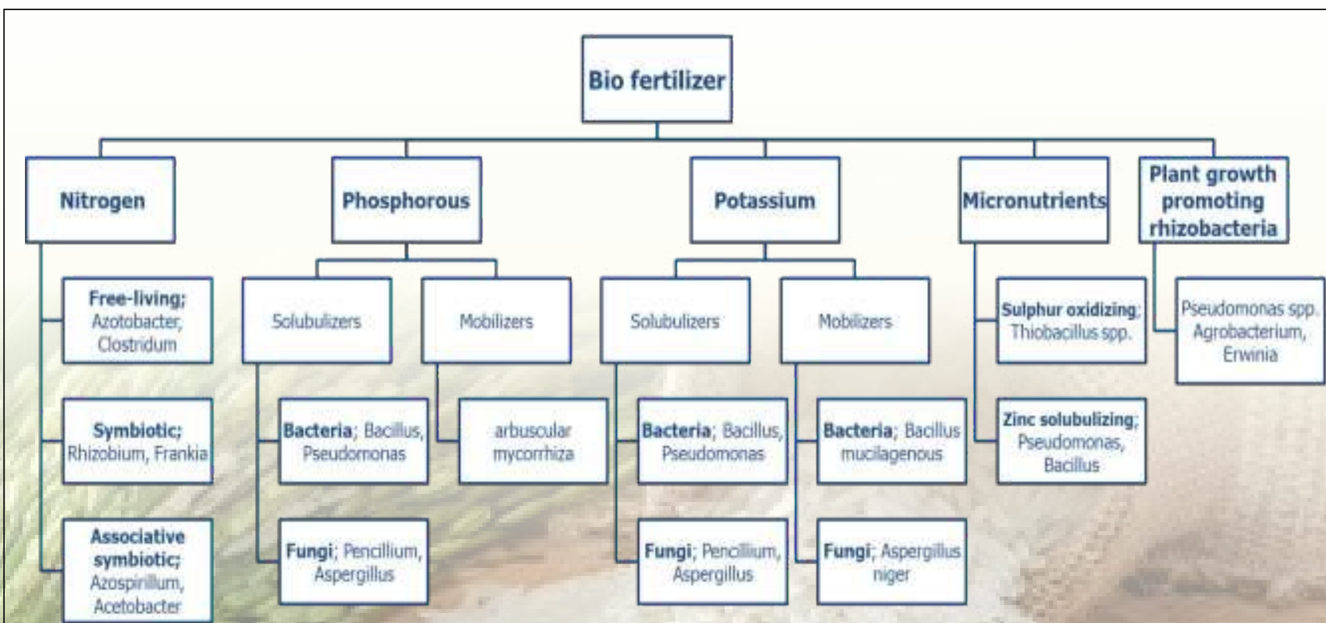

Figure 1: Classification of Bio fertilizers

• ***Azotobacter*** is a free-living bacterium that fixes nitrogen in non-leguminous crops such as rice, cotton, and vegetables. It has been shown to increase yield by 25–50 t ha^{-1} and sugar content by 10–15% in sugar cane (Meena et al., 2017).

• ***Azospirillum***, another free-living nitrogen fixer, has been used successfully in non-leguminous crops like cereals and oilseeds, fixing between 20-40 kg of nitrogen per hectare per year (Isawa et al., 2009).

• ***Anabaena Azollae,*** *Azolla* is a symbiotic bacterium primarily used for fixing atmospheric nitrogen, particularly in rice cultivation. It is typically associated with the free-floating fern *Azolla*, which harbours the nitrogen-fixing cyanobacterium *Anabaena*. The leaves of *Azolla* contain 4-5% nitrogen on a dry weight basis and 0.2–0.4% on a wet weight basis. These leaves decompose rapidly, releasing nitrogen that is readily available for plant uptake.

• ***Blue-Green Algae (Cyanobacteria)***, Nitrogen-fixing cyanobacteria are among the most widespread N2 fixers on the Earth. This group of prokaryotes, commonly known as Blue-Green Algae (BGA), includes species such as *Nostoc, Anabaena, Oscillatoria, Aulosira,* and *Lyngbya*. *Cyanobacteria* play a crucial role in enriching soil with nitrogen, while also producing essential vitamins (such as vitamin B complex) and growth-promoting substances like auxins, indole acetic acid, and gibberellic acid, all of which accelerate plant growth.

These nitrogen-fixing biofertilizers are a sustainable way to reduce reliance on synthetic fertilizers and improve soil health.

2.2. Phosphate solubilizing biofertilizers

Phosphorus is another essential nutrient for plants, but much of the phosphorus in soil is in an insoluble form that plants cannot directly absorb. Phosphate-solubilizing microorganisms, such as *Pseudomonas fluorescens* and *Aspergillus niger*, convert insoluble phosphate compounds into soluble forms that plants can take up. This can improve crop yields by 10-20% (Asoegwu et al., 2020). Mycorrhizae are fungi that form symbiotic relationships with plant roots, enhancing nutrient uptake, especially phosphorus. They increase the surface area of the root system, making it easier for plants to absorb nutrients. Vesicular Arbuscular Mycorrhiza (VAM) fungi have been shown to significantly increase plant phosphorus uptake and improve overall plant growth, enhancing tolerance to various stresses and reducing the need for chemical fertilizers.

2.3. Potassium-solubilizing biofertilizers

Potassium is a vital nutrient for plant health, yet only 1-2% of potassium in the soil is available to plants. Potassium-solubilizing microorganisms like *Bacillus* spp. and *Aspergillus niger* help release potassium into forms that plants can absorb. This enhances plant growth, increases resistance to diseases, and improves crop quality. Studies have shown that *Bacillus mucilaginosus* can improve oil content and biomass in crops like groundnuts, increasing potassium availability in the soil. Other potassium-solubilizing microorganisms, such as *Bacillus pseudomycoides*, have shown positive effects in crops like tea plants (Pramanik et al., 2019).

2.4. Sulfur-oxidizing biofertilizers

Sulfur is an essential micronutrient for plants, important for protein synthesis and enzyme activation. Sulfur-oxidizing bacteria like *Thiobacillus* species convert elemental sulfur into sulfate, a form that plants can readily absorb. These bacteria not only improve sulfur availability but also help mitigate sulfur pollution in the environment. Studies have shown that the inoculation of *Thiobacillus* bacteria can increase sulfur oxidation and enhance the availability of other essential nutrients in the soil, improving plant growth and soil health (Riaz et al., 2020).

2.5. Zinc-solubilizing biofertilizers

Zinc is an essential micronutrient for plants, but its deficiency is a widespread issue, particularly in soils that are over-fertilized or poorly managed. Zinc-solubilizing microorganisms like *Pseudomonas* and *Bacillus* species help solubilize zinc and make it available for plant uptake, improving plant growth and resilience. *Burkholderia* and *Acinetobacter* species have been shown to enhance zinc availability and boost crop yield, particularly in rice and maize (Vaid et al., 2014).

2.6. Plant Growth Promoting Rhizobacteria (PGPR)

PGPR are bacteria that colonize the plant rhizosphere (root zone) and promote plant growth by enhancing nutrient availability, producing plant growth hormones, and increasing resistance to biotic and abiotic stresses. PGPR bacteria can also improve soil fertility by decomposing organic matter and facilitating nutrient mineralization. PGPR can help plants tolerate environmental stresses like drought, salinity, and disease. They also contribute to sustainable agricultural practices by reducing the need for chemical fertilizers and pesticides. Examples of PGPR include *Pseudomonas, Azotobacter, and Bacillus*, all of which are widely used to enhance plant growth and soil health (Ilyas et al., 2020).

3. Types of Biofertilizers Used in Rice Cultivation

3.1. Nitrogen-fixing bacteria & cyanobacteria

❖ *Azospirillum* and *Rhizobium* are key nitrogen-fixing bacteria that enhance nitrogen availability in rice fields, improving plant growth by converting atmospheric nitrogen into a form that plants can use.

❖ *Cyanobacteria*, particularly in flooded rice fields, play an essential role in biological nitrogen fixation, significantly contributing to the nitrogen supply for rice crops.

3.2. Phosphate solubilizing microorganisms

❖ Microorganisms like *Pseudomonas* and *Bacillus* solubilize bound phosphorus in the soil, making it available for plant uptake. Phosphorus is crucial for optimal growth and development, especially in rice cultivation.

3.3. Potassium solubilizing microorganisms

❖ *Bacillus mucilaginosus* and *Frateuria aurantia* are examples of potassium-solubilizing microorganisms that convert insoluble potassium into plant-available forms, improving potassium availability for rice plants, thus enhancing overall growth and yield.

3.4. Plant Growth-Promoting Rhizobacteria (PGPR)

❖ PGPR bacteria, such as *Pseudomonas* and *Azotobacter*, produce phytohormones like Indole Acetic Acid (IAA), amino acids, and vitamins. These compounds stimulate root development, improve nutrient uptake, and increase stress tolerance, making rice plants healthier and more productive.

3.5. Mycorrhizal Fungi

❖ Mycorrhizal fungi enhance phosphorus uptake and improve the rice plant's resilience to drought and nutrient stress. They increase the surface area of the roots, aiding in better nutrient absorption and overall plant health.

4. Key Reasons to Promote Biofertilizers in Rice Cultivation

4.1 Enhanced nitrogen fixation

❖ Rice is a nitrogen-demanding crop, and biofertilizers like *Azospirillum*, *Azotobacter*, and Blue-Green Algae (BGA) fix atmospheric nitrogen, reducing the need for synthetic nitrogen fertilizers.

❖ Combining biofertilizers with organic amendments boosts nitrogen-use efficiency and promotes sustainable productivity in rice fields.

4.2. Improved phosphorus and potassium availability

❖ Phosphate Solubilizing Microorganisms (PSM), such as *Bacillus* and *Pseudomonas*, convert insoluble phosphorus into forms that are available for plant uptake, optimizing phosphorus use and improving rice growth.

❖ Potassium-solubilizing microbes increase the availability of potassium in the soil, leading to improved plant vigor, grain quality, and overall yield.

4.3. Better soil health and microbial activity

❖ Biofertilizers contribute to the improvement of soil organic matter, aggregate stability, and microbial diversity. This ensures long-term soil fertility and enhances plant growth.

❖ Arbuscular Mycorrhizal Fungi (AMF), for example, improve root development and water uptake, helping rice plants withstand drought and nutrient stress more effectively.

4.4. Reduced environmental impact

❖ Chemical fertilizers often lead to problems such as nitrate leaching, water pollution, and greenhouse gas emissions (e.g., N_2O from excessive nitrogen use). Biofertilizers provide slow-release, more efficient nutrients, helping to mitigate these negative environmental effects.

❖ Natural biofertilizers like BGA and *Azolla* in paddy fields reduce methane emissions and contribute to carbon sequestration, promoting eco-friendly farming practices.

4.5. Increased stress tolerance and disease resistance

❖ PGPR bacteria improve root growth and enhance plant defense mechanisms, making rice plants more resilient to diseases and abiotic stresses like drought, salinity, and nutrient deficiencies.

❖ Endophytic biofertilizers help mitigate stresses such as salinity and heavy metal contamination, making them especially beneficial in challenging rice-growing areas.

4.6. Cost-effective and farmer-friendly

❖ Biofertilizers can significantly reduce fertilizer costs, making rice cultivation more affordable and profitable for small and marginal farmers.

❖ Many biofertilizers can be produced locally, reducing dependency on expensive external inputs and supporting local agricultural economies.

5. Conclusion

As concerns about soil health and environmental sustainability continue to grow, biofertilizers offer an effective and eco-friendly alternative to conventional chemical fertilizers in rice cultivation. Their widespread adoption can reduce dependency on synthetic fertilizers while maintaining or enhancing agricultural productivity. By focusing on microbial inoculants, biofertilizers improve soil health, enhance nutrient availability, and promote better nutrient cycling, ensuring long-term soil fertility and sustainability. This shift not only reduces the negative environmental impacts associated with intensive farming practices but also helps secure future food production. Biofertilizers, including nitrogen-fixing, phosphate-solubilizing, potassium-solubilizing, sulfur-oxidizing, and zinc-solubilizing microorganisms, significantly contribute to improved crop yields and soil health. Furthermore, the use of Plant Growth-Promoting Rhizobacteria (PGPR) enhances plant resilience to environmental stress and promotes biodiversity in the soil. As global food demand rises, biofertilizers will play a pivotal role in ensuring food security while preserving the environment for future generations.

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