Editorial

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Microbial biofertilizers: Pathways toward agricultural sustainability

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The development of sustainable agricultural methods is the biggest worldwide challenge of the 21st century. The future of agriculture and the environment are seriously threatened by our over-reliance on the use of hazardous chemical fertilizers to boost productivity. Agrochemicals can be replaced with the innovative and environmental friendly microbial bioformulations technology, which opens the door to sustainable agriculture. Biofertilizers are becoming more and more popular as a healthy substitute for these hazardous chemical fertilizers with a market potential of 3.8 billion dollars by 2025. Plant growth promoting (PGP) microorganisms based biofertilizers have shown a number of benefits in agricultural practices, including improved soil fertility, biotic and abiotic stress control, and environmental friendly nutrition. The application of biofertilizers is a sustainable and eco-friendly substitute that prevents eutrophication, increases product flavor, taste, and odor, and enhances fertility by lowering soil acidification. However, its widespread commercial use has been hindered by a number of its drawbacks, such as vitality, efficiency, adaptability, and inconsistency. Numerous strategies have been used to enhance and get around these limitations. By combating these limitations, biofertilizers can noticeably contribute toward environmental friendly farming practices, emphasizing their significance in achieving sustainable agriculture system and improvement of long-term soil health.

Agriculture and agricultural products have been our sole source of existence since human evolution [1]. To maintain a healthy lifestyle, the vast majority of people on the planet depend on agriculture for food, feed, other essentials, and secondary products with therapeutic value. To address the growing population's hunger needs, researchers, agricultural experts, and agro-industries should develop appropriate sustainable agricultural practices [2]. Managing agricultural operations to a degree that can effectively eradicate the need for hunger is the primary goal of any civilized empire. Traditional agricultural practices only provide food and feed on a residential scale. Only the farmer's families and the local village communities possess access to traditional ways. Agricultural practices are evolving in a surprising way these days as people are more concerned with protecting the environment and focusing on the agricultural system to maximize agro-productions using different types of microbial biofertilizers [Figure 1]. In farming processes, different hormones, chemical fertilizers, and other synthetic minerals are used to increase crop yields. The health of the soil and the plant system are both impacted by synthetic chemicals and minerals. While greater chemical use may lead to increased output, the depletion of vital minerals and other nutritional components might occasionally function as a barrier [3].

A sustainable agricultural system can be developed in a way that safeguards the environment and preserves the ability of future generations to meet its own needs. Overuse of chemical fertilizers depletes the environment because residues that function as secondary pollutants may find their way into food webs and chains and eventually into human bodies [4]. Secondary pollutants may linger in the environment for a comparatively longer time due to their health-hazardous consequences. A new phase of industrialization might be ushered in by the use of biofertilizers in place of chemicals in the agricultural sector [5]. The word bio-formulation can be represented as the development of components incorporating living but effective microbial strains, using appropriate carrier substances for their beneficial application in agriculture, industry, and bioremediation [Figure 2]. A physiologically active component of microbial biomass and its metabolites combined with the carrier material constitutes a bioformulation. It can be employed in environmentally benign ways as a nutrient acquisition tool, biocontrol agent, and plant growth promoter. These bioformulations fall into one of the following categories: Solid, liquid, and encapsulated. Solid bioformulations offer the required bacteria a protected and nutrient-rich environment after field treatments. It improves storage efficiency and lowers the probability of contamination. It consists of powders, granules, and water-dispersible granular formulations with binders, carrier material, and active substances [6].

Aqueous suspensions, or liquid formulations, are made up of biomass suspensions in either water, oil, or both. It is composed of 35–65% carrier liquid, microorganisms 10–40%, suspender 1–3%, dispersion 1–5%, and surfactant 3–8% [7]. During production, distribution, and storage, liquid bioformulations assist keep organisms stable. It boosts persistence and provides protection against abiotic environmental influences. Liquid bioformulations fall into one of four categories: Oil dispersion, ultralow volume suspension, oil-miscible flowable concentrate, or suspension concentrates [8]. The liquid carriers could be polyvinylpyrrolidone, fruit juices, broth, water, or jaggery syrups. By combining solid active components that are stable to hydrolysis and weakly soluble in water, the suspension concentrates have been formed [9]. This mixture is easy to pour for spraying, quantifiable, and non-dusty. Therefore, liquid bioformulations serve as a great carrier to stabilize the bioinoculants during manufacture, transport, and long-term storage, as well as extending the shelf life of products [10].

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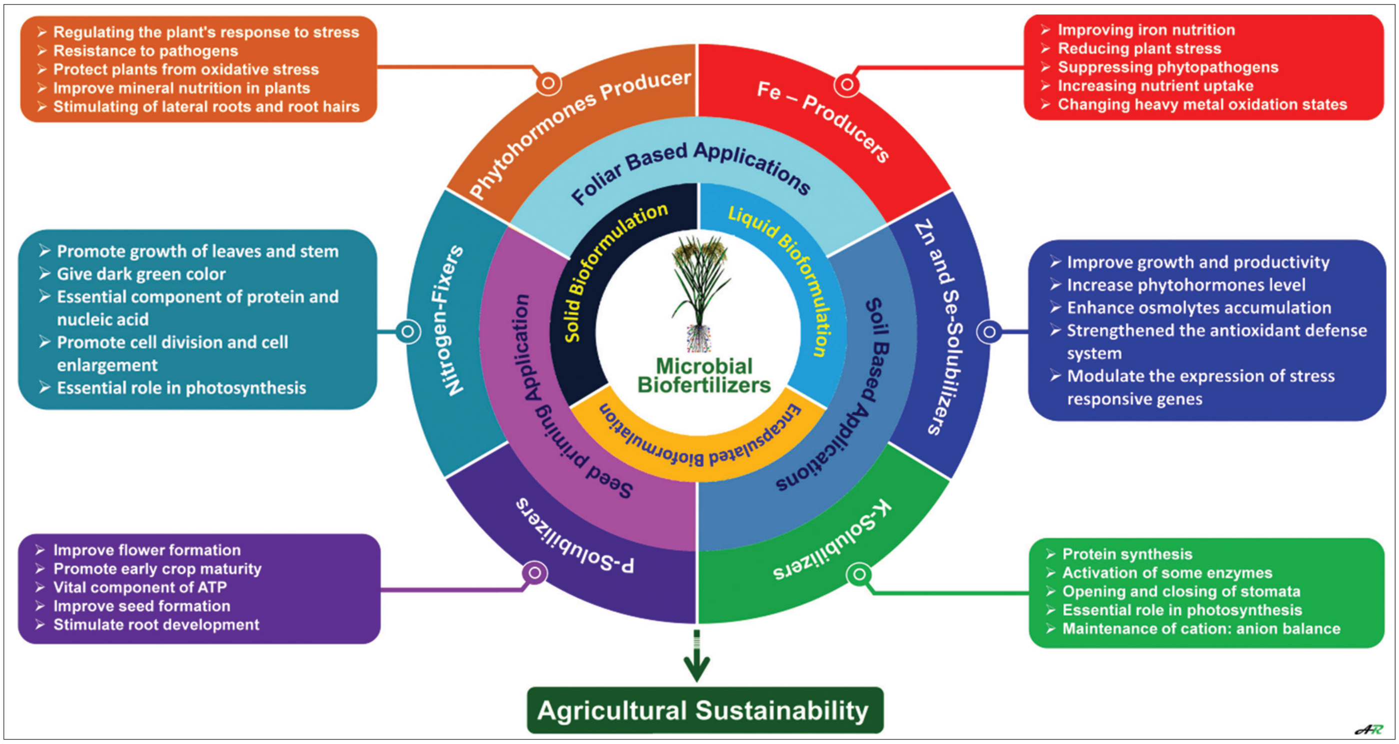

Figure 1: Microbial biofertilizer types, inoculation methods, and roles of different biofertilizers for agricultural sustainability.

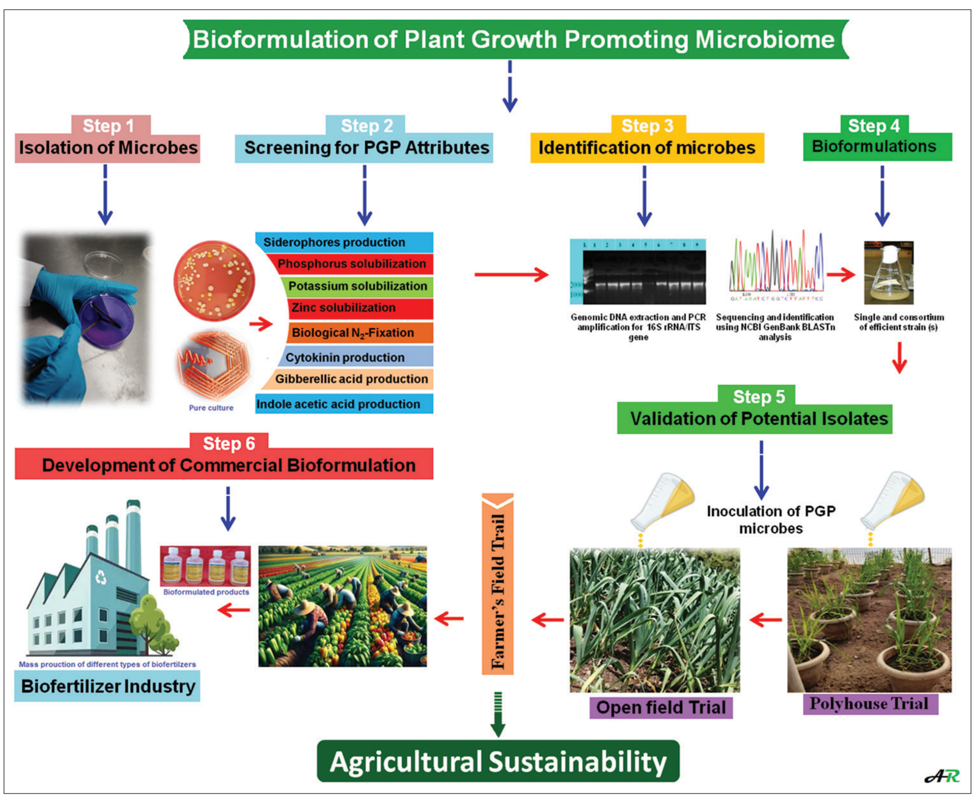

Figure 2: Microbial bioformulation strategies for development of novel biofertilizers for agricultural sustainability. Adapted with permission from Negi *et al*. [6].

In light of restricted techniques during the creation of bioformulations, there are only a few ways to administer microorganisms to crops. At present, there is a variety of equipment for applying micro-based fertilizers, including spinning drums, mixers, and sprayers [11]. These devices differ from industrial to field, which affects the labor time and cost of applying bioinoculants. Typically, bio-inoculants are applied in three ways including, soil, plant, and seed treatment [10]. This approach is more practical for farmers since it shields little or delicate seeds from harm and covers larger areas faster, but it is costly and typically requires a lot of inoculants [12]. Applying a variety of bacterial species to the soil increases the probability that the inoculant will interact with the rhizosphere, hence promoting better plant growth. A solid, liquid, or encapsulation-based bioformulation can be used to treat soil. When used in soil inoculation, granular carriers such as peat, charcoal, perlite, or other soil components have proven positive results [8]. Inoculants have also been successfully put directly to the soil in the form of powder, slurries, and liquids. This method involves applying a bioformulation utilizing granular applicators, hand sprayers, or mechanical sprayers to the top surface of the field's moist soil before seeding [13]. Although soil treatment can also be applied to standing crops, in these situations, bioinoculants may not be evenly dispersed. To protect plants from invading areas, soil treatment is more advantageous when dealing with soil-borne phytopathogens. This technique has various limitations in large application due to cost, large quantities of inoculants and the obligation of specific equipments [12].

Seed treatment is most common bioinoculants appliance method as it required a reasonably small quantity of bioinoculants [14]. Seed inoculation method delivered microbes directed to the rhizospheric region, or in the case of endophyte, these microorganisms enter interior part of plant and expand an intimate plant-microbe interactions [15]. Seed treatment method done using a number of way including, seed coating, seed soaking, and bio-priming. Seed coating method is commonly done by making slurry of carrier based inoculum and uniformly mixing slurry into the seeds [16]. This method offers several advantages, such as being cost-effective and requiring only a small quantity of inoculants. However, it also has certain limitations, including the short shelf life of microbes, reduced endurance, and limited inoculum coverage on seeds. Hence, the selection of delivery method depends on available tools, shape and size of seed, and the console and economical for the grower [17]. Microbial inoculums enhance growth and plant development by direct or indirect mechanism. The direct mechanism of PGP microbes is the major step involved to support plant growth in a forward and direct including N_2-fixation, solubilization of phosphorus nutrients (N, P, K, and Se), and increasing iron (Fe) availability [18,19]. These PGP mechanism influence growth of plant directly but the influence vary from strain to strain as well as species to species. Due to enhancement of particular ion fluxes at root surface, PGP microbes directly enhance nutrient uptake. Growth regulators known as phytohormones stimulate plant growth development by influencing morphological and physiochemical process at low concentrations [20,21]. Various microbial formulations have been reported for enhancement of plant growth in various crops by following several mechanisms. A study reported that, microbial bioformulation of three compatible strains *Rahnella* spp. (N_2-fixer), *Bacillus tropicus* (phosphorus solubilizer), and *Bacillus megaterium* (potassium solubilizer) improve the growth of wheat plant [22]. Another study reported that, application of Zn solubilizing bacterium, namely, *Brevibacillus brevis* increase growth of wheat *Triticum aestivum* [23]. A study documented that, siderophores producing bacterium identified as *Spinacia oleracea* improve nutrient uptake [24]. Another study document that, Se solubilizing bacterium, namely, *Bacillus mycoides* identified through 16S rRNA and application of this bacterium enhance growth of wheat plant [23].

Opportunities for sustainable agriculture are presented by the commercialization of biofertilizers. Nevertheless, the journey from lab experiment to the commercial use of such biofertilizers is filled with difficulties. The efficient selection of microbial strains is one of the main obstacles [25]. The widespread adoption and commercial use of biofertilizers have been impeded by various restrictions including lower nutrient content supply as compare to chemical fertilizer, deviation in its storage efficacy and external environmental conditions such as temperature, light and humidity [26], inappropriate microbial strains, inadequacy of quality assurance, inappropriate carrier materials, untrained and inefficient staffs [27], imperfect inoculation methods, and low volume production, strain mutation and market accessibility are the main drawbacks in the large scale production and commercialization or biofertilizers [28,29].

Furthermore, environmental protection organizations in both developed and developing nations have very strict registration requirements for microbial compositions, and the associated expenses are expensive. Due to this, industrialists are frequently discouraged from pursuing their commercialization and most commonly, and most of the time the laboratory research does not result in useful outdoor applications. In close connection with this, quality assurance concerns significantly impede the commercialization and use of biofertilizers [30]. Given these opportunities and obstacles, interdisciplinary research is desperately needed to bridge the knowledge gap between lab results and field applications, enabling biofertilizers to reach their full potential in environmentally friendly and sustainable agriculture [31]. Research on the creation of biofertilizers is being conducted extensively worldwide in an effort to support agronomic sustainability. Some microorganisms used as biofertilizers have recently been found to exhibit opportunistic pathogenic behavior and fall under the biosafety level 2. These pathogenic microbes pose significant risk to human health and the environment [32]. Potential PGP bacteria are typically not tested for their pathogenicity and biosafety; instead, they are said to be helpful only when testing for traits that promote plant development. Unfortunately, it has been found that certain endophytic and rhizosphere plant growth-promoting bacteria (PGPB) contribute to a number of diseases. Moreover, these PGPB can transfer their virulence and multidrug resistance genes to other bacteria in the environment by horizontal gene transfer [33].

There is no denying that agriculture is essential to the continuation of life on Earth. However, it is no longer sustainable to use artificial fertilizers carelessly and continuously. Therefore, it is crucial to look at the efficient delivery systems of biofertilizers in order to actually replace agricultural chemicals and improve the sustainability and productivity of agriculture. Using creative delivery methods, bioformulations can effectively reach their target regions, increasing their positive effects on crops and lowering the requirement for conventional chemical treatments. Biofertilizers have the potential to be the most valuable resources for sustainable agricultural practices and crucial tools for ensuring food security, protecting the environment, and creating a sustainable world if they are thoroughly researched, commercialized, and used. By encourage the wider acceptance and incorporation of bioformulations into farming practices, we can move toward environmental friendly and productive agricultural systems that contribute to food safety and environmental health.

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