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Contribution, Limitations and Future of Plant-Growth Promoting Consortium in Sustainable Agriculture

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Abstract

Current agricultural methods rely significantly on chemical fertilizers, pesticides, and other agrochemicals to enhance plant growth and combat pathogens, aiming to boost crop yields. However, the accumulation of chemical residues in the soil diminishes soil fertility considerably over a period. These accumulated chemicals gradually alter the soil's chemical composition, ultimately rendering it infertile. The high-risk conditions associated with these agricultural chemicals such as bioaccumulation, chemical toxicity and development of resistance in pathogens is leading to increased awareness and acceptance of sustainable agricultural practices promoting usage of more organic options including microbial alternatives as plant growth promoting microbes. Contemporary agricultural methods prioritize the utilization of biological agents for enhancing plant growth and controlling pests with aim of sustainable soil management, as these are cost effective and ecofriendly. Extensively publicized and scientifically investigated, plant growth-promoting microbes offer promising solutions to enhance crop yield and also provide a better alternative to conventionally used agricultural chemicals. Many such commercial biofertilizers and bio pesticides are available in market, which are cost effective and ecofriendly too. Despite these qualities, market penetration and acceptability of these bioinoculants are limited. The present study explored major limitations of existing bioinoculants, major hurdles affecting formulation quality, gap between potential market demand and production, concepts of consortia to produce synergistic effects, and challenges in consortia-based formulation development. The present study also presented solutions to overcome these bottlenecks so that these bioproducts can help to reduce the toxic chemical load in soils augmenting the soil health and prove to be a valuable and better acceptable option for sustainable agriculture.

Keywords: consortia, bioformulations, biopesticides, biofertilisers, bioinoculants, sustainable agriculture

INTRODUCTION

Soil is a complex and dynamic mixture of minerals, organic matter, and a home for innumerable living organisms. Understanding the properties of soil, both inorganic and organic, is essential for effective soil management. The combination of these properties determine soil fertility, structure, and suitability for various agricultural and environmental purposes. Understanding the microbial community in soil is essential for sustainable agriculture, environmental conservation, and maintaining soil fertility. Research continues to explore the complex interactions between below ground soil microorganisms, plants, and environmental factors to enhance our ability to manage and preserve soil health.

Increasing incidents of chemical abuse in agricultural soils is primarily because of unguarded and unscientific reliance on agrochemicals. While the intention of the farmer is progressive, the practices followed however and misguided

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implementation is eroding soil health and soil quality (Figure 1). Shifting completely away from chemical input-based agriculture is an impossibility, gradual substitution with organic and microbial supplementation can be the way forward for both agriculture and soil health (Figure 2).

Though farmers are opening up to the use of microbial alternatives that are less costly and eco-friendly, the market penetration and acceptability of these bioinoculants are limited [1]. The primary constraints associated with current biofertilizers include their predominantly single-species nature, which often caters to isolated benefits, focusing either on macronutrients (NPK) or micronutrients or solely providing biocontrol and that too with a host-specific bias. Requirement of specific storage conditions, contaminations and presence of chemical additives (binder, adjuvant etc.) in formulations are other major hurdles affecting inoculum quality (Figure 3).

Many studies have been done to explore whether the various different organisms providing growth promotion and safeguard against pathogens can provide synergistic plant growth advancement and biocontrol; and whether consortia of such organisms per se can tolerate and provide shielding effect against residual pesticides that may otherwise compromise efficiency of bioinoculant. Thus removing existing issues and increasing acceptance of effective and eco-friendly growth promoting microbial-based options, is a significant mandate of agriculture scientists today.

INFLUENCE OF CURRENT AGRICULTURAL PRACTICES

Today, the demands of growing population are pressing our natural resources which are exploited to the maximum for higher production to provide goods and services to more than 8 billion humans of the world [2]. Since 1950, the human global population has been on a steady rise, and according to UN forecasts, it is projected to reach 9.2 billion by the year 2050 with an estimated requirement to increase existing food production by 70% to feed this population. This steeply increasing food demand places incessant pressure on agricultural systems for production/yield increase. Due to the finite nature of land resource available, the cultivable land for agricultural use is limited. only 20% expansion of arable land is possible by 2050, rest 80% of required agricultural production needs to be compensated only through an increase in the agricultural yield. In India itself, the production of food grains increased more than four times in less than five decades that is, 50.82 million tons in 1950–1951 to 211.2 million tons by the year 2000. Almost 3% growth in crop production was recorded in the 1970s due to chemical intensive, technology-driven agricultural practices of green revolution.

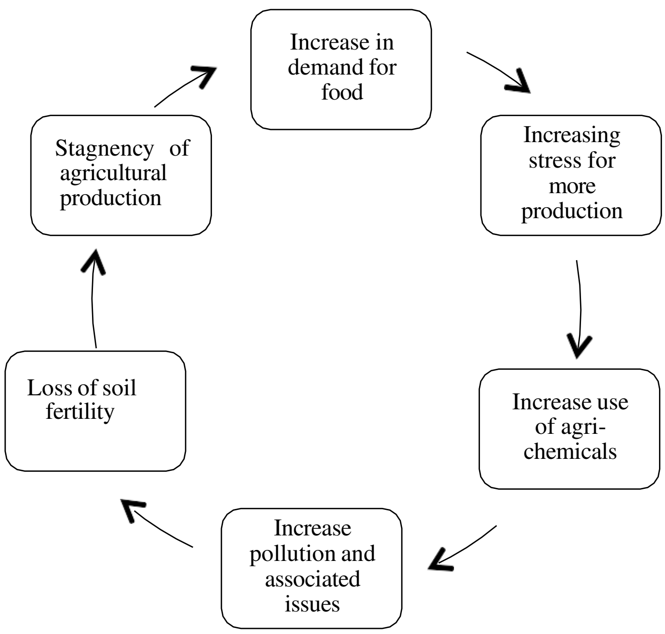

Figure 1. Current agricultural scenario: Vicious cycle of resource exploitation.

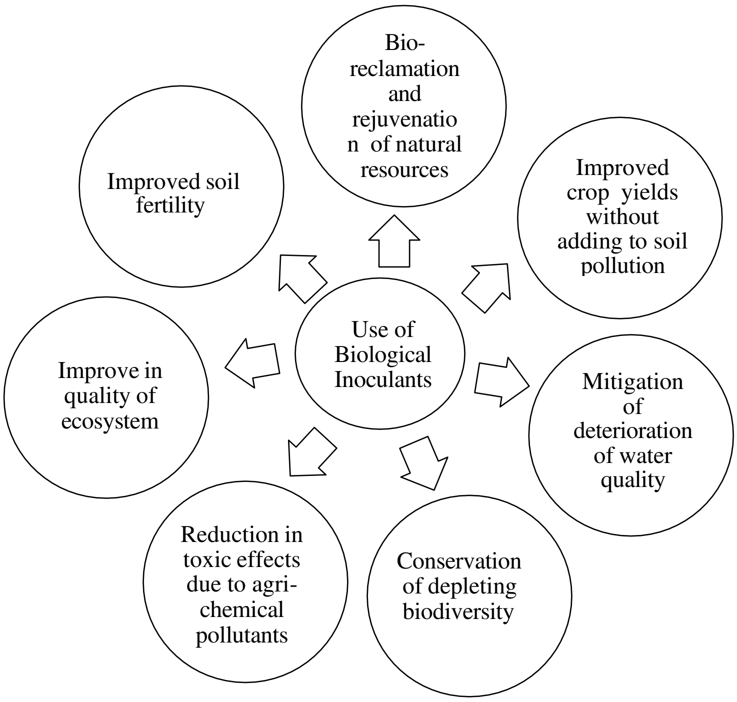

Figure 2. Role of biological inoculants in agriculture.

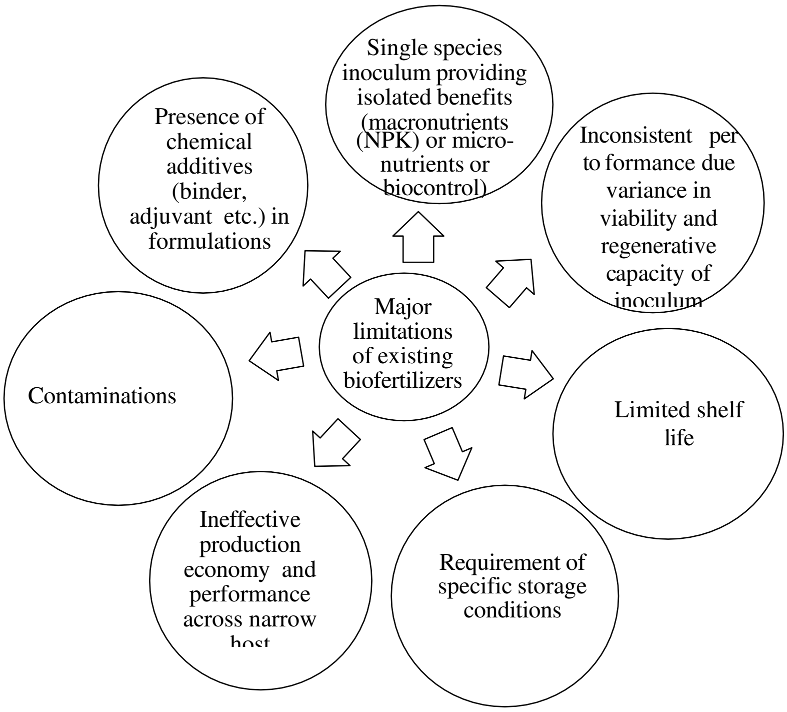

Figure 3. Major limitations of existing biofertilizers.

Since then such high external-input agriculture using inorganic fertilizers, pesticides, and other amendments has become a norm in order to increase agricultural production worldwide. However, globally this growth increase was followed by a plateau of growth in yield during last few decades reporting decline in growth yield from 3.2% per year in 1960 to 1.5% in 2000 and predicted 0.9% in the coming decades of 2050 for major cereal crops as per the Food & Agriculture Organization (FAO) estimates. Food grains production in India is reporting stagnant production trends at 257 million tonnes in last two decades [3–6]. These global trends showed a decelerating yield rates despite absolute increase in yield over the past five decades and that too after using improved cropping techniques, fertilization and irrigation. This is an indication of reaching saturation limit.

Global use of nitrogen fertilizer has recorded a seven-fold increase, and phosphorus usage has recorded a 3.5-fold increase from 1960 to 2000, with another three-fold increase expected in consumption of both types of fertilizers by 2050. This is happening though, returns in term of efficiency of yield are diminishing with increasing application at global level [3, 4, 7]. Only 30–50% of applied nitrogen and phosphorus fertilizers are taken up by crops and rest of the chemicals are lost to ecosystem. Similarly, 99% of pesticides used for crop treatments are also wasted and end up in the environment. These unintended, erroneous agricultural applications of chemical fertilizers and pesticides brought about many environment-related problems such as causing soil and aquatic pollution, loss of soil quality, loss of soil and aquatic biodiversity and other environmental problems due to bioaccumulation and/or biomagnification. Leaching of excess fertilizers and pesticides is reportedly the major source of nutrient and toxic loading of global aquatic systems. This human-induced soil degradation (Figure 1) was reported to have caused loss of productivity (>15%) in cultivated lands and add more pressure to limited agricultural land [8, 9]. Soil organic matter levels in India are also experiencing a rapid decline due to intensive use of chemical input. The cost of soil degradation due to increasing intensity of cultivation and inadequate and inappropriate application of fertilizers ranges from Rs. 0.6 billion to Rs. 3.4 billion annually [10]. Ironically, decreasing soil fertility drives a farmer with commercial interest increasingly towards chemical fertilizers, worsening the soil situation further and converting more and more fertile agricultural soils to marginal lands with near zero productivity (Figure 1).

Further, these difficult to degrade and accumulated chemical residues left in soil after cropping not only limit water and soil health but also enter the food chain causing harm to herbivores, animals, and human health directly. Reduction in biodiversity also occurs in non-agricultural systems, as an indirect impact of these accumulating agrichemicals which change the species composition of ecosystem [8]. Additionally, the dwindling variety of plant species cultivated for commercial purposes since the inception of agriculture and domestication over 7000 years ago [11] has contributed to biodiversity loss. These effects have been exacerbated by population growth and the increasing mechanization and specialization of farming practices, significantly impacting our ecosystem.

NEED FOR LOW CHEMICAL INPUT AGRICULTURE SYSTEM

The biggest challenge faced by agricultural scientists today is to increase food production for growing human population on constrained land areas using the limited available resources [5, 6]. The global pressure to increase agricultural production and yield resulted in more reliance upon chemical inputs in agriculture involving excessive and unrestrained usages of chemicals provided as fertilizers and pesticides. Though these chemical-based agricultural practices are credited with increased productivity, associated health hazards, pollution, deterioration of quality in natural resources along with their increasing costs are becoming causes of serious concern. The negative impacts due to abuse of present high external inputs- based agricultural system poses many crucial environmental challenges [3, 4, 12] such as degradation of natural soil resources, stagnant crop yields, deterioration of water quality due to agrochemical pollution, depleting soil-biodiversity, toxic health effects on human and livestock, loss in quality of ecosystem etc. These concerns have necessitated the search for a supplementary means to reduce chemicals input in agriculture.

Thus, finding an effective solution to these problems with sustainable exploitation of natural resources and with no compromise in food production is the real challenge to agriculturists presently. In the present scenario, exploring and employing new environmentally sustainable agricultural techniques including concept of organic agriculture and precision agriculture based on principals of sustainability is no longer an option but an imperative step [8, 9, 13]. Studies comparing conventional and modern agricultural systems have shown that organic farming would be able to feed all human population by 2050 [14]. Thus one of the currently required objective of development of sustainable agricultural strategies is to enhance the long-term fertility and productivity of the soil at economically sustainable levels. Achieving this goal involves aligning the supply of soil nutrients with the nutrient requirements of plants through greater reliance on biological inoculants (Figure 2) along with judicious and discriminate use of chemical fertilizers for promoting plant growth and production. Biocontrol agents need to be recommended to control the soil borne plant pathogens thus reducing pesticide consumption and contributing to increased host productivity [15, 16]. Among many different options available to improve present agricultural practices and soil management, some techniques such as plant growth-promoting microorganism (PGPM) inoculation to plants for growth improvement and the utilization of bio-control agents for disease and pest management has become a well-established practice, frequently employed by farmers; though their potentials are widely under utilised.

MULTI-PRONGED APPROACH FOR IMPROVING PLANT GROWTH

As stated in European commission report [17], a bio-based technology option comprises of a broad range of technological solutions (already available or still to be developed) using renewable biological resources (plant, animal and microbial), for improving plant growth and production for sustainable development (Figure 4). The potential advantages of this technology encompass a shift towards a lower carbon economy and sustainable production practices, fostering a resilient and sustainable food chain that contributes to global food security with use of recommended agricultural practices.

The chemical elements and compounds that are essential for growth and metabolism (viz. plant nutrients) not only influence plant growth but also the physicochemical nature of soils [18, 19]. Established agricultural practices provide required nutrients to crops mostly in soluble chemical forms that plants can use immediately. This approach of nutrient supplementation through fertilization results in nutrient runoff with no possibility to build long-term soil fertility. In contrast, substantial organic agricultural practices append the soil with large reservoirs of slowly-releasing nutrients such as poultry waste, cattle dung, soya meal kelp, legume crop residues etc. Resulting microbiological activities lead to nutrient recycling and slow release of minerals and plant nutrients thus complementing plant requirements for longer periods of time avoiding use of chemical fertilizers and pesticides [20]. These low-cost technologies help in restoration of soil fertility, soil-biodiversity and avoid pollution while producing quality foods.

Further, genetic erosion due to selection for higher yield in crop plants made modern cultivars causing approximately 32% of yield reduction due to various biotic and abiotic stresses. Thus the priority of plant breeders recently shifted to breed stress-resistant crops. Conventional breeding methods for developing stress resistance require longer time and labor and non-availability of resistance sources, transfer of non-desirable genes along with resistance genes during hybridization, are associated major problems [21]. Many modern breeding methods have been developed to overcome the above-mentioned problems such as:

Mutation Breeding: Introducing inheritable mutations in crop plants to select resistant mutants against a particular stress;

Targeting Induced Local Lesions in Genomes (TILLING): A cost effective reverse genetics tool to discover the genes involved in the stress tolerance mechanism against various biotic and abiotic stresses;

Marker-Assisted Selection (MAS): To select desirable plants for breeding programmes based on DNA markers linked to various economically important traits.

These molecular breeding tools reportedly made the selection processes accurate and efficient [22].

Transgenic approach to develop genetically modified (GM) crops with exotic genes inducted from discrete species through recombinant DNA technology lead to a new era of agro-technology. The advancement of disease and insect resistance in plants stands as a crucial application of the transgenic approach. Notably, the introduction of chitinase genes encoding chitinase enzymes in plants to degrade fungal cell walls as a broad resistance mechanism, along with the incorporation of the *Bt* gene to produce toxins for resistance against various chewing insects, represents significant milestones achieved through this technological innovation. Although the global cultivation of transgenic crops has increased 40 times from 1.7 million ha during 1996 [21, 23]; these crops still face biosafety and regulatory issues with limited acceptance specially in developing countries.

Despite all these technical advances, developing resistant plant varieties and commercializing them is time consuming and cost intensive method. Moreover, new and improved cultivars might be required to be released regularly as it can be challenging for a single cultivar to sustain resistance over an extended period against varied abiotic stress in different regions worldwide. Further, pests and pathogens species also vary regionally and keep evolving which may enable them to avoid the plant's resistance response. These technologies are high-input agriculture, with very high energy costs associated, thus limiting its implementations.

MICROBES AND THEIR CONTRIBUTION TO VARIOUS ASPECTS OF PLANT GROWTH PROMOTION

Microorganisms play a crucial role in agricultural systems, particularly the category of beneficial microbes known as plant growth-promoting microorganisms (PGPMs). These microorganisms have the potential to enhance soil quality, increase crop production and protection, preserve natural resources, and ultimately establish a more sustainable and secure agricultural environment [16, 24–27]. Use of environment friendly biotechnological approaches such as the application of PGPMs is considered as a promising option for improving crop yield [16, 25–27], and to promote soil fertility via nutrient mineralization plus nutrient and organic matter cycling as well as help to maintain ecosystem health.

PGPMs studied for their plant growth promotion potential can be grouped as:

1. PGPMs providing nutritional benefits; and
2. PGPMs providing non-nutritional benefits.

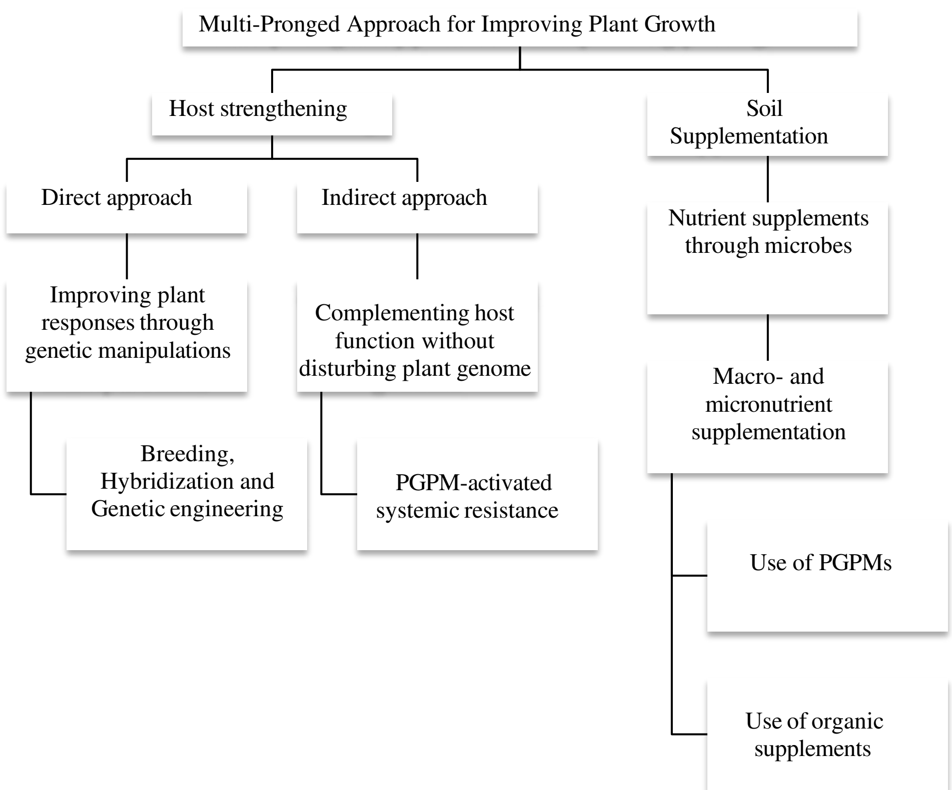

Figure 4. Multi-pronged approach for improving plant growth.

PGPMs PROVIDING NUTRITIONAL BENEFITS

PGPMs are symbiotic and non-symbiotic bacteria acting as biofertilizers, helping in nutrient cycling, or providing nitrogen (N_2) supplementation (*Rhizobium* sp.), or phosphate (P) solubilizers (mycorrhizal fungus) or providing other nutrient supplements such as hormones, minerals, organic anions for better metabolization of nutrients and also help to retain these nutrients in soil system as species of diazotrophs, species of Enterobacteriaceae and other organisms involved in Nitrogen cycle [16, 25–27].

PGPMs Providing Nitrogen

Plants absorb N_2—an essential macronutrient—in the form of mineral ions that is, either as nitrate (NO_3^-) or as ammonium (NH_4^+) ions mainly. Almost 50% of N_2 supplied as chemical fertilizers is believed to be wasted due to volatilization, denitrification and leaching thus polluting the environment especially ground water. Thus, biological N_2 fixers are gaining importance as N supplements [8, 9, 18]. Rhizobia are the most reported symbiotic N_2-fixers. Other symbiotic N_2-fixers associated with legumes and non-leguminous plants are species of: *Allorhizobium, Azorhizobium*, *Bradyrhizobium, Frankia, Mesorhizobium,* and *Sinorhizobium* providing for 65% of N requirement of plants globally [28, 29]. The process of symbiotic N_2-fixation exclusively depends upon the presence of key enzyme nitrogenase controlled by nitrogen fixing (*nif*) genes and the nodule formation in susceptible hosts is under the influence of nodulation (*nod*) genes. *Azotobacter* species such as *A. chroococcum, A. virelandii,* and *A. beijerinckii*; and *Azospirillum* species such as *A. brasilense, A. lipoferum, A. amazonense, A. doebereinera,* and *A. irakense* are amongst the most reported free-living N_2 fixing bacteria studied for their plant growth promotion effects. Other commonly occurring free-living diazotrophs studied for their N_2 fixing ability are *Acetobactor diazotrophicus, Burkholderia* species (*B. vietnamiensis, B. kururiensis, B. tuberum, B. phynatum, B. brasilensis, B. unamae, B. xenovorans, B. tropica, B. tropicalis, B. phymatum, B. tuberum*), *Azoarcus* species (*A. communis, A. indigens, A. tolulyticus, Azoarcus* sp. BH, *Entrobactor* species (*E. radicincitans, E. cloacae* MSR1, *E. ludwigii*), *Gluconobactor* species (*G. johannae* and *G. azotocaptans*), *Azotobactor, Herbaspirillum, Ralstonia taiwanensis, Nathania salitolerans, Asaia bogorensis,* and *Pseudomonas* sp., obligate anaerobic heterotroph *Clostridium* sp. etc., also provide N_2 nutrition and are associated with various steps in biological N_2 fixation [30, 31]. As biological N_2 fixation is a high energy requirement process, the N_2-fixing capacity demonstrated by bacteria under *in vitro* conditions need to be tested in detail under greenhouse and field studies before classifying such N_2-fixer bacteria as bioinoculants.

PGPMs Solubilizing Phosphate

Phosphorus (P) is a crucial nutrient for plant growth, serving as a structural component in essential molecules such as nucleic acids and adenosine triphosphate (ATP), and participating in vital metabolic pathways such as biological N_2 fixation and photosynthesis [18]. While P is abundant in soils, plants face P scarcity because they can only absorb it as monobasic (H_2PO_4) or dibasic (HPO_4^{2-}) forms. Both inorganic and organic forms of P show high reactivity and forms insoluble complexes with Fe, Al, and Ca and precipitate rendering it unavailable to plants [32].

Mycorrhizal fungi such as *Glomus, Paraglomus, Sclerocystis, Acaulospora, Enterophosphora, Gigaspora, Scutellospora, Geosiphon,* and *Archaespora*, play a significant role in increasing P mobilization either through solubilization or by enhancing access to distant P reservoirs via fungal mycelia [32].

Phosphate solubilizing bacteria (PSB) are a subset of PGPMs that possess the ability to solubilize sparingly soluble phosphates through specific enzymes and excreted organic acids, siderophores, and protons. These bacteria include members of the *Bacillus* species (*B. megaterium, B. coagulans, B. subtilis*), *Microbacterium laevaniformans*, *Pantoea agglomerans*, *Pseudomonas putida, P. fluorescens*, *Burkholderia cepacia*, *Serratia marcenscens*, *Klebsiella, Kluyvera, Streptomyces, Rhodococcus, Arthrobacter, Delftia, Chryseobacterium, Gordonia, Phyllobacterium, Herbaspirillum, Advenella,* and *Tetrathiobacter*. [32–34].

The biocontrol fungus *Trichoderma harzianum* has also demonstrated P solubilization along with other plant-growth-promoting traits [35]. Additional microorganisms with P-mobilizing functions include Penicillium (*Penicillium bilaiae, P. radicum, P. italicum*) and Aspergillus species (*Aspergillus flavus, A. niger, A. fumigates, A. awamori,* and *A. terreus*) [34]. These microorganisms employ various mechanisms to solubilize P, enhancing the availability of nutrients, including iron, to plants. Ultimately, their positive impact on plant growth stems from their ability to increase nutrient.

PGPMs Producing Phytohormones

Phytohormones are organic signalling molecules including hormones such as indole acetic acid (IAA), gibberellic acid (GA), abscisic acid (ABA), cytokinins; metabolites such as ACC-deaminase and other substances such as ethylene gas. These compounds are synthesized by plants through regulated mechanisms in very low quantities and play a fundamental role in plant growth and development. Apart from plants, many plant-associated bacteria are also known to produce these phytohormones which act as chemical messengers (between the host and the microbes) and have their impact on biochemical, physiological and morphological processes in plant growth. Various reports are available demonstrating plant growth stimulating impact of PGPMs through production of these phytohormones or other metabolites in the plant.

Indole Acetic Acid (IAA)-Producing PGPMs

Plant-associated bacteria are producing auxin phytohormones particularly IAA. IAA production by PGPMs influences various aspects of plant development, including improved seed germination, increased root length, and enhanced root biomass. Both pathogenic and growth-promoting bacteria can produce IAA. Phytopathogenic bacteria mainly use the indole acetamide pathway for IAA production causing tumor induction in plants whereas plant growth promoting beneficial bacteria mainly utilize the acid indole pyruvic pathway. Species of *Azospirillum* lead the pack of best IAA producers. Other example include *Aeromonas, Azotobacter, Bacillus, Burkholderia, Enterobacter, Grimontella, Klebsiella, Pantoea, Pseudomonas, Rahnella, Rhizobium*. *In vitro* studies with PGPMs established correlation between IAA releasing activity of the microbes viz-a-viz plant growth capabilities. Thus *in vitro* screening for IAA production can be a useful method for initial selection of PGPMs for potential bioinoculants [33, 36, 37].

Gibberellic Acid (GA)-Producing PGPMs

Gibberellins are tetracyclic diterpenoid acids specially known to regulate bud dormancy and delay of senescence in combination with other phytohormones. GAs are also involved in seed germination and development of seedling, stem and leaf growth, floral initiation, flower and fruit growth in plants. Many fungi and bacteria including *Achromobacter xylosoxidans, Azospirillum brasilense, A. lipoferum, A. diazotrophicus, Acetobacter diazotrophicus, Bacillus pumilus, B. subtilis, B. halotolerans, B. licheniformis, Bradyrhizobium japonicum, Fusarium moniliforme, Gibberella fujikuroi, Herbaspirillum seropedicae, Rhizobium meliloti, Rhizobium leguminosarum,* produce gibberellins as secondary metabolites. The positive effects of GA help in assisting improved seedling vigor, better root and shoot growth, increase grain yield and dry matter production in host plants. These effects can be attributed to better nitrogen incorporation, total carbohydrate accumulation and alleviation of water stress conditions due to interaction with other hormones [36]. A deeper exploration of microbial–plant interactions is essential to understand the physiological significance and mechanisms underlying the actions of bacterially produced plant hormones, particularly GAs.

Cytokinin-Producing PGPMs

Cytokinins, purine derivatives, play a vital role in regulating cell division and differentiation of meristematic tissues in higher plants. Many vital processes such as chlorophyll accumulation and senescence delay, as well as leaf initiation and organ formation are impacted in conjunction with other plant hormones. Various PGPMs, including bacteria such as *Rhizobium sp., Bradyrhizobium, Bacillus subtilis, B. pumilus, Brevibacterium halotolerans, Pseudomonas putida, Azospirillum* sp., alongside fungi, have been identified as capable of synthesizing cytokinins-like compounds. Their inoculation leads to increased availability of cytokinins, both externally and internally, in host plants, resulting in significant growth benefits similar to those observed with auxins [36]. This underscores the potential of cytokinin-producing PGPMs in enhancing plant growth and development.

Ethylene-Producing PGPMs

Ethylene is a crucial gaseous plant hormone, regulating fruit ripening, senescence, and stress responses [8, 36, 38]. Although limited reports exist on ethylene production by PGPMs, *in vitro* studies have identified *Azospirillum*, *Azotobacter*, and *Bacillus* species as potential ethylene producers. PGPM inoculation enhances ethylene levels in host plants, possibly due to cross-talk between bacterial IAA and ethylene synthesis pathways [33–37, 39]. However, elevated ethylene levels may even have negative effects on host plant. Hence, further understanding of microbe-induced ethylene, its role and additional mechanisms involved and influencing the overall impact of microbe-induced ethylene on plant–microbe interactions need to be researched.

Abscisic Acid (ABA)-Producing PGPMs

ABA is a stress regulator hormone produced by higher plants and confers the ability to adapt to stresses. Very limited literature is available about PGPMs-producing ABA and their impact on plant growth and development. Some PGPMs such as *Azospirillum brasilense, Achromobacter xyloxosidans, Lysinibacillus fusiformis, Bacillus pumilus, B. subtilis, B. licheniformis, Brevibacterium halotolerans,* and *Pseudomonas putida* have been reported to produce ABA in culture media. PGPM inoculation to plants has also been reported to enhance ABA concentration [36] though role and impact need to be understood.

Thus, looking at overall picture about the phytohormones production by PGPMs and the role of microbially produced phytohormones to regulate the plant growth promotion, only IAA has been studied in detail. Production of GA by PGPMs and its growth positive impacts on plants are also reported at places. Production of cytokinins, ABA and ethylene by microbes are scantly documented leaving a wide scope open to study and understand related plant–microbe interactions and role of microbe produced phytohormones on plant growth.

PGPMs PROVIDING NON-NUTRITIONAL BENEFITS

These include biocontrol agents which protect plant against pathogenic organisms or microbes providing tolerance to abiotic factors such as pH, temperature, salinity, drought or resistance to metal or chemical pollutants.

PGPMs Providing Abiotic Stress Relief

Inoculation with some PGPMs induce physical and chemical changes that enhance tolerance to abiotic stress in plants. These beneficial microorganisms trigger production of stress-related hormones such as ethylene, abscisic acid, cytokinin or other metabolites such as jasmonic acid, salicylic acid etc., to elicit transcript profiles associated with tolerance/defense/resistance mechanisms [27, 31, 40].

Notable PGPM inoculants demonstrating stress protection abilities are *Alcaligenes xylosoxidans, Arthrobacter, Azospirillum, Bacillus, Flavobacterium, Ochrobactrum anthropi, Pantoea agglomerans, Paenibacillus polymyxa, Pseudomonas fluorescens, P. putida, P. stutzeri, P. mendocina, P. mallei, P. alcaligenes, P. pseudoalcaligenes, P. diminuta, P. chlororaphis, P. extremorientalis, P. aureofaciens, P. aurantiaca, Rhizobium, Serratia marcescens, S. plymuthica, S. rhizophila*. These microorganisms have demonstrated protective responses in various crop plants under stress conditions [5, 30, 41].

PGPMs have been reported to alleviate various stress conditions such as drought, salinity and osmotic stress, chilling or heat stress; resulting in increased germination, better shoot/root length, dry matter production and yield. PGPMs conferring abiotic stress resistance also improve plant responses against pathogenic colonization thus conferring protection against both abiotic and biotic stresses. This involves a complex response mechanism stimulating various metabolic activities through production of phytohormones, synthesis of higher amounts of stress hormone ABA, decreased ethylene levels by the action of enzyme ACC deaminase, or through other metabolites and biochemicals. Release of exudates, exopolysaccharides by bacterial actions also improve quality of rhizospheric soil allowing plants to thrive better [16, 30, 41, 42]. While much research has concentrated on the plant growth-promoting effects of PGPMs, their role in combating environmental stress need to be explored in detail.

PGPMs Providing Biotic Stress Relief

PGPMs enhancing plant growth via suppression of phytopathogens, nematode pests and pathogenic protozoans, thus providing relief against biotic stresses, are termed as biocontrol agents or antagonists. *Trichoderma* are well known biocontrol fungi and its many variants are available in the market as biocontrol agent. Other microbes known for their biocontrol activities are, bacterial genera namely, *Bacillus*, *Burkholderia*, *Lysobacter*, *Pantoea*, *Pseudomonas,* and *Streptomycese*; and fungal species such as *Ampelomyces*, *Coniothyrium*, *Dactylella*, *Gliocladium*, and *Paecilomyces* [16, 27, 43–45].

Soil-borne plant pathogens along with pests and weeds are responsible for 10–30% yield losses in Indian agriculture. Most widely practiced methods to control these soil-borne pathogens rely upon using chemical insecticides/pesticides/fungicides. These chemicals have associated high-risk conditions such as chemical run-off/bio-accumulation, chemical toxicity and development of resistance in pathogens and are cost intensive as well. Thus use of bio-based biocontrol agents proposes an alternative environment friendly natural control of plant disease for crop yield improvement [16, 46, 47].

Biocontrol agents use a variety of mechanisms caused by pathogens such as release of antibiotics, fungal cell wall-lysing enzymes, siderophores, hydrogen cyanide (HCN) etc.

Many PGPMs of bacterial origin for example, *Bacillus, Burkholderia, Lysobacter, Pantoea, Pseudomonas, Streptomyces*, and of fungal origin for example, *Trichoderma, Gliocladium, Ampelomyces, Coniothyrium, Dactylella, Paecilomyces,* nonpathogenic *F. oxysporum, Heteroconium chaetospira*, are well reported for their biocontrol activities [13, 16]. Various mechanisms involved in suppression of pathogens to counter biotic stress can be grouped as: (i) direct mechanisms namely antagonism due to production of antibiotics, siderophores, HCN, hydrolytic enzymes (chitinases, proteases, lipases), which suppress the growth of pathogens; and (ii) hyper parasitism or indirect mechanism acting by competing with the pathogen for space and nutrients. Biocontrol process can also activate systemic resistance responses in plants via modification of plant hormones [33], thus minimizing disease impact on plants. An interplay of these mechanisms may help to systematically designed strategically to limit usage of chemical and support integrated pest management efforts as a part of sustainable agricultural systems.

Other Plant Growth Promoting Mechanisms of PGPMs

Microbes having ability to degrade and decrease chemical loads may provide environmental-friendly effective solution to the problem of soil health deterioration [27, 48, 49].

Plant growth promoting mechanisms employed by PGPMs incorporate various less studied mechanisms and integrated approach, leading to diverse cross talk among different methods resulting in growth promotion of plants.

One such system involves deaminase (1-aminocyclopropane-1-carboxylate deaminase) production ability that is a key enzyme in ethylene metabolism. Under environmental stress (cold, drought, flooding, pathogen infection, heavy metals), plants synthesize ACC, which is then converted into ethylene, leading to poor growth. PGPMs such as *Alcaligenes sp., Bacillus sp., Ochrobactrum, Pseudomonas sp., P. fluorescens*, *P. migulae*, and endophytic *Bacillus phytofirmans* that possess ACC deaminase enzyme degrade ACC to NH_3 and α-ketobutyrate thus blocking the ACC availability to plant for ethylene production and related toxic effects in plants. These bacteria also use ACC excreted from plant roots as a nitrogen source for their own metabolism, giving them an advantage in the plant rhizosphere. Such activities in bacteria also contributes to stress tolerance, including salt and drought stress in plants [33, 37, 48, 50].

The excretion of siderophores by bacteria is another well studied mechanism known to trigger plant growth either directly (improved Fe nutrition) or indirectly (by out competing phytopathogens through Fe sequestration). Iron is an essential micronutrient for both plants and microorganisms. Under aerobic conditions when iron solubility is low, PGPMs such as *Azospirillum brasilense, Bacillus, Bradyrhizobium, Burkholderia, Citrobacter, Enterobacter, Grimontella, Herbaspirillum, Klebsiella, Pseudomonas, Rhizobium, Stenotrophomonas, Streptomyces, Serratia,* etc., secret siderophores. Under Fe limiting conditions, Fe^{3+}chelating or binding ability of microbial siderophores enhance plant growth by providing utilizable Fe to the host. Fe sequestration by PGPMs also creates Fe depletion for pathogenic microbes thus limiting their growth [13, 33, 37] and supporting plant growth indirectly.

Several bacterial species including *Arthrobacter, Azospirillum, Bacillus, Pseudomonas, Serratia,* and *Stenotrophomonas* produce NO and volatile organic compounds (VOCs). Metabolites such as nitric oxide (NO), VOCs, polyamines, jasmonates etc., acts as an intermediary in IAA-induced root development that are involved in improving plant growth and induce systemic resistance (ISR) towards pathogens influencing increase in plant biomass, disease resistance, and abiotic stress tolerance directly and/or indirectly [13, 36].

Certain diazotropic species and Pseudomonads reportedly produce Vitamin B; for example, biotin, niacin, riboflavine, thiamine with a documented evidence to plants has been documented to favour root development indicating growth promoting role of these bacterial products. Polyamines such as spermidine, spermine etc., produced by some PGPMs such as *Azospirillum brasilense* are low molecular weight organic compounds which serve as growth regulators associated with root growth promotion and stress tolerance. Many PGPMs such as *Rhizobium leguminosarum, Bacillus pumilus, Achromobacter xylosoxidans,* and *Pseudomonas fluorescens*, has been reported to induce ISR via jasmonate pathway [36, 47].

Thus, PGPMs play a multifaceted role in plant health, from growth promotion to stress mitigation to pollution degradation. Further research in this area could uncover additional benefits and to design strategies for sustainable agriculture.

NEED AND SCOPE FOR DEVELOPING PGPM-BASED INOCULA

Biofertilizers and biopesticides are the low-cost sources for providing plant nutrients and disease control, respectively. Commercial production of biofertilizers started with *Rhizobium* culture 'Nitragin' launched by Nobbe and Hiltner, in 1895. The endeavor to popularize and commercialize biofertilizer started extensively during 1990s when the Ministry of Agriculture set up of the National Project on Development and Use of Biofertilizers (NPDB) under the Ninth Five Year Plan [51, 52].

In order to promote the use of bioinoculants efficiently and aggressively in agriculture, the limitations of existing bioinoculants and scope of improvements in bioinoculant research should be considered first.

LIMITATIONS OF EXISTING BIOINOCULANTS

Biofertilizers and biopesticides offer economic and ecofriendly alternatives to chemical fertilizers, supporting sustainable agriculture by promoting plant growth and increasing yields while minimizing environmental pollution [13, 36]. Despite decades of knowledge and documented benefits in literature, the biofertilizer industry has not achieved the expected popularity [40, 47]. The utilization of PGPMs in agriculture remains limited globally, despite their efficacy in enhancing plant growth and yield improvement due to various reasons (Figure 3).

Most of the commercially available formulations are single species inoculum catering for isolated benefits and that too with host-specific bias. Likewise biocontrol agents though offer protection and increased yield without contaminating natural resources, provide control over limited species of pathogens that too incoherently [53–56]; compared to chemical pesticides [13, 14, 43].

Effectivity of bio-inoculants varies largely depending on environmental factors and soil characteristics. Availability of nutrients and organic matter, soil acidity or alkalinity, presence of agrochemicals and change in cropping pattern affects their performance drastically [48, 57]; thus, making these techniques less trustworthy and limiting their acceptance. Further, limited shelf life with specific storage requirement, variance in viability and regenerative capacity of inoculum and problem of persistence in environment added to these limitations. Thus, while bio-inoculants offer potential benefits, addressing these challenges is crucial for their successful implementation in enhancing crop yields [51, 52].

PRESENT MARKET SCENARIO

Population of India is growing at a compound annual growth rate (CAGR) of ~1.4% with a concomitant increase in food demand. The area under cultivation for food grains is continuously sinking from approximately 126.9 million hectare in 1980s to 121.1 million hectares only in 2010. Further annual wheat and rice yield is reported to be stagnant at 3 metric ton/hectare since 2000 despite increase in total production [5] and increase in chemical fertilizer consumption due to which ~22% demand shortfall of food items is projected in near future [17]. These problems associated with non-sustainable modern agricultural systems and resulting challenges are affecting soil–crop environment, microbial ecology and related distortions to natural ecosystem balance. In addition to economic impacts due to increasing cost of cultivation, stagnant income of farmers, dwindling issues of food security and safety are matters of serious concern [51, 52]. Introducing safe and economical biobased technologies needs to be the top priority to bring about substantial improvements in agriculture management. This may also lead to sustainable and sufficient output in terms of agricultural production and yield improvement. The application of PGPMs, increasing use of organic manures, restrained use of mineral fertilizers, crop rotations, efficient irrigation in dry areas and sufficient drainage in wet areas are some of the practical, scientifically studied and proven techniques that can offer positive impacts on soil quality and soil organism densities. Moreover, improvement in plant growth and increased yield are being addressed with minimal adverse impact on environment when PGPMs are opted as a solution.

For long, varieties of PGPMs have been studied and many of them have been developed and used as commercial biofertilizers and biopesticides including the species of *Azobacter, Azosprillum, Bacillus, Pseudomonas, Rhizobium, Trichoderma* etc., reducing the exclusive burden on chemical inputs [36]. These PGPM-based formulations promise of attractive technology-supported solution that enhance crop yield. Growing awareness both in the farming community and consumers about detrimental effects of chemicals used in agriculture present exponential growth opportunity to biofertilizers and biopesticides market as reflected in >12% CAGR growth that is, from approximately $7.1 billion in 2012 to $14 billion by 2019 in global market [1].

The biofertilizer market in India is occupied by both the public sector and private sector units. The Indian biofertilizer market is worth $110.07 million in 2022 and is expected to grow to $243.61 million by 2029, exhibiting a growth of 12.02%.

Biobased agriculture market is fast growing market segment controlling 16% market share in global biotech industry amounting to $227 billion in year 2012 and is continuously expanding at a CAGR of 11.8% in five-year duration. Asia leads the global biotechnology market with Indian contribution at approximately 1.2% which is at $306 billion. In 2008, Indian biotechnology market was $2.6 billion which grow to be $25 billion by 2015 with a CAGR of 31.5%. Of this growing biotechnology market, Indian bioagriculture market share was estimated to be of $330 million in 2008 (12% of Indian biotechnology market) as compared to $23 million in 2002 showing CAGR of approximately 55%. In this, biofertilizers owned approximately $110.07 million in 2022 and is projected to reach $243.61 million by 2029, at a CAGR of 12.02% within less than a decade period [17, 58]. Despite impressive increase in production in the last decade (↑44833 tons), only around one third of the estimated demand potential for biofertilizers in the country is as yet met. This huge gap between potential market demand and estimated production provides great opportunity for biofertilizer market [59, 60]. Investment of the Government of India in biotechnology sector also increased from $133M in 9th plan to $1392M in 11th plan (CAGR >350%) providing immense scientific as well as economic growth opportunities [17]. Thus the future of PGPM-based bioinoculants seem very promising and offers both economic and ecological advantages.

Despite impressive increase in production in the last decade (2005 metric tons in 1992–1993 to 37997.61 tons in 2009–2010), only two third demand potential for biofertilizers in the country is accomplished as yet. This huge gap between potential market demand and production provides great opportunity for biofertilizer market. Considering the factors discussed above, there is a vital need for a better and improved PGPM-based bioinoculants to accelerate the demand and acceptance in already growing niche for biotechnology based agro-market.

SCOPE OF IMPROVEMENTS IN BIOINOCULANT RESEARCH

An ideal PGPM-based bioinoculant should enhance plant growth potential, have an extensive spectrum of action, possess high rhizosphere competence, be compatible with indigenous soil microflora, be able to tolerate environmental stresses on inoculation and should be safe for the environment [13, 43]. In conjunction with all the above-mentioned qualities, bioinoculant microbes should be fast growing, persistent, low cost, easy to produce, and easy to apply. They should also be least dependent on environmental conditions to maintain their virulence, comparable in effectiveness and compatible with agrochemicals and safe for environmental application.

Traditionally, varieties of PGPMs have been used and many of them are available as commercial formulation and are very helpful in reducing role of chemicals in agriculture. Nitrogen fixers and phosphate solubilizers are most well studied bioinoculants capturing more than 90% market segment of bioinoculant production. Other players in the market are biocontrol agents such as *Trichoderma* species; potash and phosphate solubilizers such as *Frateuria aurantia*; Zn and S mobilizers such as *Thiobacillus* species and Mn solubilizer such as *Pencillium citrinum.* These are amongst the most prominent commercially available bioagents [37, 43, 51, 61].

Nevertheless, the growing biofertilizer markets seek alternatives capable of providing more comprehensive benefits as compared to single-species, narrow-host range biofertilizers. The notion of employing a combination of microbes to deliver broader, non-specific growth promotion across various host types and overall soil health enhancement is becoming increasingly significant. Within a consortium, certain microbes may facilitate nutrient mobilization and release growth hormones in the rhizosphere, increasing the availability of NPK, while others may offer protection against root pathogens, thereby contributing to holistic plant growth. Such diverse community of beneficial bacteria using distinct resources in rhizosphere also provide less available niche for invading pathogenic species hence better protection. Researchers are now focusing to test the beneficial effects of consortia combinations of species, and if greater microbial diversity improves plant health in large-scale field trials, it might ultimately help in reducing chemical loads in intensively cultivated agricultural fields [13, 43].

POTENTIAL FOR PLANT-GROWTH PROMOTING BACTERIAL CONSORTIUM

In nature, microbial organisms evolve symbiotically, interact with each other, and perform various agroecological functions. In the agricultural field, using a combination of diverse microorganisms has garnered attention recently for their ability to perform various ecological functions such as soil bioremediation, plant growth promotion, and pest/disease suppression.

A bacterial consortium is a biofertilizer containing carefully selected two or more compatible microbial strains that may or may not naturally occupy the same ecological niche [62, 63], to provide synergistic or additive plant growth promotion. Bacterial consortia have been shown to enhance beneficial traits in plant performance and symbiotic processes in rhizospheric soils as compared to individual strains, owing to the diverse array of plant growth promotion and biological control mechanisms they encompass. The utilization of these consortia represents a viable strategy for enhancing drought resistance, mitigating soil salinity, improving nutrient uptake, managing pests, and combating phytopathogenic infections in agricultural crops [25, 26, 43, 64]. Furthermore, certain bacterial consortia exhibit nitrogen-fixing abilities, convert inaccessible nutrients into assimilable forms, and produce phytohormones, among other functions.

Combining microbes with different modes of action, nutritional needs, and growth characteristics such as PGPMs with pest protecting microbes are proposed to have more beneficial synergistic impact on plant growth promotion as compared to single microbial strain (Figure 5). This approach reduces application costs, enhances soil–microbial biodiversity in plant environments, yet faces challenges such as microorganism incompatibility, competition from native organisms, and habitat adaptation hurdles [65, 66]. The utilization of 'microbial consortia' in agriculture, hold promise in reducing reliance on nitrogen fertilizers, aiding carbon sequestration, alleviating drought stresses, and contributing to sustainable agricultural practices amid the anticipated growth in biopesticides and biostimulants.

Despite the growing acceptance and utilization of microbial consortia, detailed field studies remain limited. In this context, we explored recent applications and future prospects of microbial consortia in sustainable agriculture, emphasizing the necessity for research efforts aimed at understanding the intricate interactions among various microbial communities in the environment.

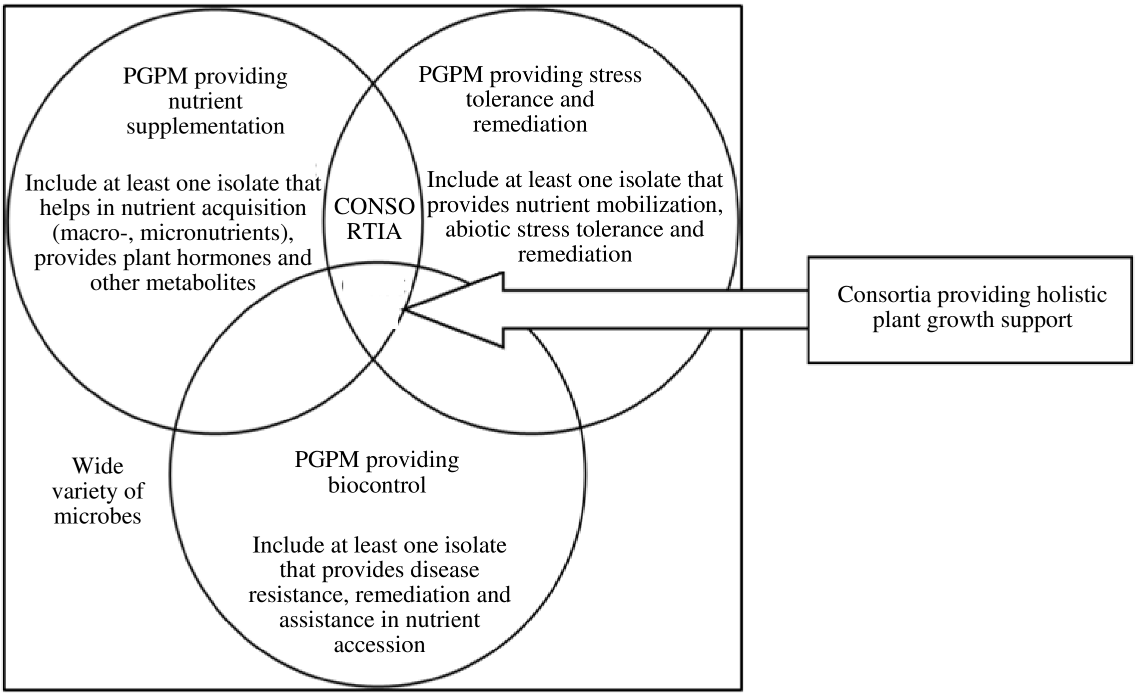

Figure 5. Figurative representation of consortium.

DIVERSE TYPES OF CONSORTIA

Plant root system colonize various microorganisms influencing plant yield, health, and nodulation [66]. Synergistic combination of different strains of single type of microbes providing diverse benefits are based on various strategies that is, niche complementarity, differential metabolic impacts and benefits etc. They are divided into two major categories as a) Consortia including single group of microorganisms; and b) Consortia including different groups of microorganisms (Figures 6a & b).

Consortia Including Single Group of Microorganisms

These may further be subcategorised into two types as described below:

Consortia of Free-Living PGPR

Bacillus safensis NBRI 12M, *B. subtilis* NBRI 28B, NBRI 33N, NBRI 53L, *Jeotgalicoccus huakuii* NBRI 13E, *B. stratosphericus* NBRI 7a, *Erwinia* sp. (EU-B2SNL1), *Chryseobacterium arthrosphaerae* (EU- LWNA-37) and *Pseudomonas gessardii* (EU-MRK-19), *P. putida, P. fluorescens, B. thuringiensis* and *P. synxantha*, *S. griseoviridis*, *B. pumilus*, *B. azotofixans*, *B. licheniformis*, *B. megaterium*, *B. polymyxa,* and *B. subtilis* [67–69].

Combination of Non-AM Fungi

Trichoderma atroviride (LX-7), *T. citrinoviride* (HT-1); *T. koningiopsis* NBRI-PR5 (MTCC 25372*)* and *T. asperellum* NBRI- K14 (MTCC 25373), *T. asperellum* ICC 012 and *T. gamsii* ICC 080, *T. atroviride* LU668 and LU297, *T. virens* LU753, *T. koningii* and *T. harzianum, T. asperellum*, *T. atroviride, T. harzianum,* and *P. lilacinus, T. harzianum,* and *Saccharomyces cereviseae* [70, 71].

Consortia of AM Fungi

Beauveria bassiana, Funneliformis mosseae, F. constrictum, Gigaspora margarita, and *Rhizophagus irregularis* (Figure 6a) [72].

Consortia Including Different Group of Microorganisms

Different combination of types of microbes also provide additive effects together and may be designed based on many of the strategies that is, additive metabolic assistances, different functional traits that regulate the growth benefits of individual strains and then combining them in one consortium. For instance, combining a microbial strain having antimicrobial activity with a soil-borne biocontrol agent or a combination of more than one of such strategies such as:

Consortia of Rhizobia and PGPR

Combination of *Sphingomonas paucimobilis*, *Microbacteria* sp., *Brevundimonas vesicularis*, *Pseudomonas rubrisubalbicans,* and *Alcaligenes eutrophus* [73].

Consortia of AM Fungi and PGPR

Bacillus sp. (CP4 e AHP3) and mycorrhizal fungi; *Piriformospora indica* (DSM 11827 and *Azorhizobium caulinodans* (B81176); *Glomus* spp. and *Bacillus* sp.; *Glomus versiforme* and *Bacillus methylotrophicus* [74–77].

Consortia of Non-AM Fungi and PGPR

Brevibacterium halotolerans (Sd-6), *Bacillus subtilis* (Ldr-2), *Achromobacter xylosoxidans* (Fd-2), *Burkholderia cepacian* (Art- 7) and *Trichoderma harzianum* (Th); *Trichoderma asperellum* (GDFS1009) and *Bacillus amyloliquefaciens* (1841); *T. harzianum* (OMG16) and *Bacillus* spp.; *T. viride* and *P. fluorescens*, *Bacillus licheniformis* (MN718157) and *Aspergillus violaceofuscus* (MH220545) [78–81].

Consortia of AM Fungi and non-AM Fungi

T. harzianum, Beauveria bassiana and *Metarhizium anisopliae*; *Macrophomina pseudophaseolina*, *Trichoderma afroharzianum*, *Trichoderma longibrachiatum, Paraphoma radicina* [82, 83].

Consortia of AM and Non-AM Fungi and PGPR

T. viride, P. fluorescens and micorryzes.

Consortia of Non-AM Fungi, Rhizobia and PGPR

Trichoderma, *Azotobacter*, *Azospirillum*, *Rhizobium* and *Pseudomonas* (Figure 6b).

These microbial consortia in agriculture, incorporating fungi, bacteria, rhizobacteria are used for plant growth promotion, plant disease control, nematode control, arthropod control and/or also be used to improve soil fertility, NPK requirements, cation exchange capacity, and mitigate abiotic stresses [67, 79, 84, 85].

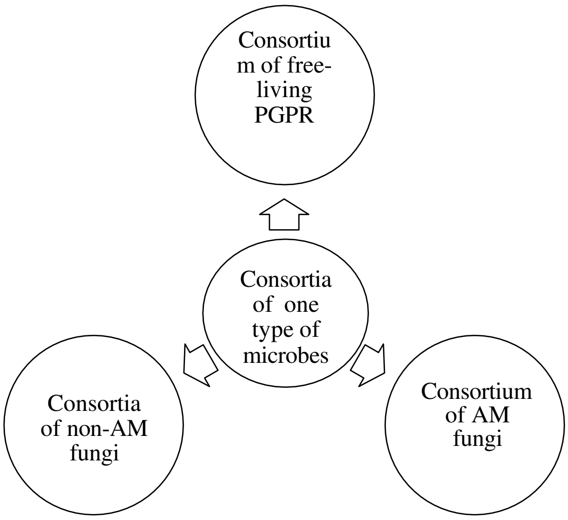

Figure 6a. Consortia including single group of microorganisms.

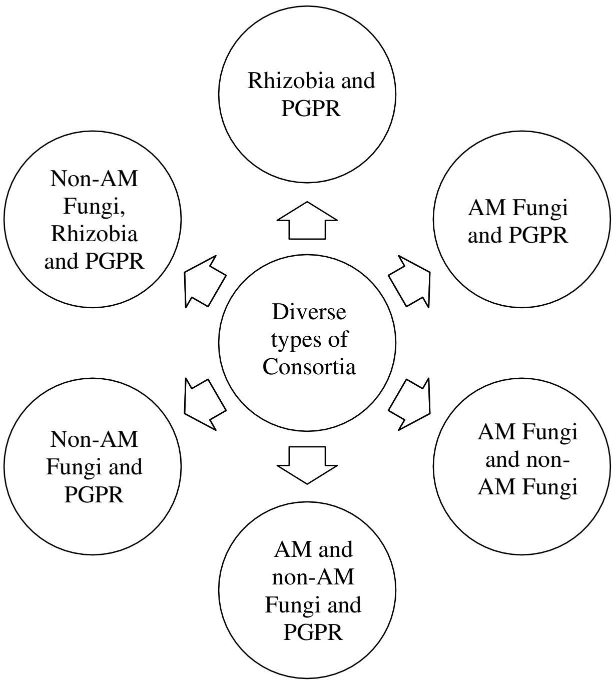

Figure 6b. Consortia including different groups of microorganisms.

EXISTING CONSTRAINS AND FUTURE OF CONSORTIUM IN SUSTAINABLE AGRICULTURE

The first and the major constraint affecting efficacy of microbial inoculants in soil is the survival and propagation of adequate numbers of applied inoculants. Thus correct formulation is crucial, providing favorable microenvironment temporarily, to prevent the rapid decline of applied microorganisms in soil

[86]. Focus on targeted application strategies on delivering the right inoculant amount to the right place at the right time, considering reliability, ease of use, logistics, cost, compatibility, and optimal timing for plant growth promotion need to be considered. New approaches such as micro-encapsulation, nanoencapsulation, fluidized bed coating, liposome entrapment etc., should be assessed to develop formulations with lengthier shelf lives [28, 43, 86, 87] and reliable field performance for commercialization. Incorporation and standardization of such technology for industrial and field applications beyond laboratories need to be pursued.

The resistance of soil microbial communities to external microorganism invasion, due to limited nutrients availability and overlapping niches, is another major hurdle. Increasing the diversity of microbial species in consortia may improve outcomes, but not necessarily always due to various other plant–soil–rhizospheric interactions. Host specificity or specificity of microbial function in consortia combination can effectively eliminate the competition from indigenous microflora promoting the dominance of the inoculant strain [57].

Inconsistency in soil structure and physicochemical properties presents another challenges for microbial inoculants, with factors such as neutral pH, moisture, organic carbon, and low salinity favoring colonization and persistence to exert required impact. Knowledge of soil nutrient status is crucial for effective inoculant use, especially concerning N, P and C levels. Amending unfavorable soil conditions before inoculation is also recommended, considering microbial adaptability limitations. Soil disturbances and strategic cultivation could also impact native microbial balance, warranting further exploration of their potential impacts in favour of inoculant microbes or reduce the impact of antagonists enhancing inoculant efficacy [58]. Thus future agronomists need to comprehend the nexus between crops, climatic conditions, and nutrients for developing competent consortia combinations.

The advancement of biofertilizer technology depends significantly on developing efficient plant growth-promoting strains. Investigation on K solubilizers is lagging way behind N-fixers and PSB although K is equally important macronutrients for plant development. More research in this field is required to create and promote balanced consortia combinations in future.

The utilization of genetically-modified inoculants, which are anticipated to exhibit enhanced efficiency in stimulating plant growth and delivering targeted impacts, is also advocated. Naturally chosen strains can be manipulated or genetically engineered strains can be used in combination for enhancing the expression, field efficiency and shelf life of future consortium. Though proving the safety of such strains and convincing society and regulatory authorities will be a major hurdle that agriculturists need to overcome. In future, establishing a global database will be another groundbreaking step to help improve technological advances. Use of multi-omics approaches can be incorporated for formulating suitable consortia for particular soils and crops based on such inventory.

Despite the constraints, forecasts suggest that the current global market for biofertilizers, estimated at approximately US$396 million in 2018, is assumed to proliferate into a thriving US$5 billion industry by 2031 [88]. Furthermore, ongoing investigations aimed at isolating, identifying, and evaluating the potential of PGPMs to serve as consortia combinations for bio-inoculants are also expanding. It is, therefore, realistic to foresee a golden opportunity for bio-inoculants as consortia to be used for advancement of sustainable crop production systems.

CONCLUSIONS

The present review highlighted the current use and limitations of microbial bio-inoculants, emphasizing their potential in sustainable agriculture despite hurdles in the market. It discusses the synergistic effects of consortia and proposes solutions to overcome obstacles, underscoring their ability to promote plant growth, control pests, and improve soil health by reducing chemical inputs. Challenges in selection, production, and application of consortia are presented alongside their future potential in agriculture.

Efforts to utilize bio-based resources aim to reduce reliance on external inputs in agriculture, promoting self-sufficiency while minimizing waste and pollution without compromising global food security. Achieving this requires research, technological development, and widespread technology transfer across stakeholders. However, changes in production practices may impact food security if not integrated properly. Therefore, exploring options to increase productivity while maintaining trust among farmers and consumers is crucial.

Challenges associated with synthetic microbial consortia in agriculture include complex interactions, regulatory uncertainties, scalability issues, and ethical considerations. Overcoming these requires interdisciplinary collaboration, improving production scalability, ensuring stability in various conditions, and addressing societal implications. Despite these challenges, microbial consortia offer tailored solutions for specific crops and holistic plant health management.

The future of bio-inoculants depends on developing efficient plant growth-promoting (PGP) consortia with improved performance and standardizing their use for industrial and field applications. Continued research is needed to advance biofertilizer development and promote their adoption in sustainable agriculture.

Implementing sustainable agricultural practices is vital in the 21st century, with rhizobacterial biofertilizers offering significant contributions. While their usage is low, further development can unlock their substantial market potential. Researchers and institutions play key roles in advancing biofertilizer development and addressing regulatory and social concerns. However, more research is needed to understand their interactions with resident microorganisms and potential negative effects.

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