Editorial

Journal of Applied Biology & Biotechnology Vol. 14(1), pp. 1-4, January-February, 2026
Available online at http://www.jabonline.in
DOI: 10.7324/JABB.2026.288288ED

Microbial resources: Untapped treasure for agricultural sustainability

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The agricultural and allied sectors play a significant role in causing widespread environmental devastation, threatening the very existence of life on Earth. Negligent application of agrochemicals frequently ruins crop yields, leading to insufficient global food production. It also leads to the accumulation of heavy metals and harmful chemical components that impact agricultural organisms across various ecosystems. Industrialization, urbanization, and population growth will have progressed to the point where environmental preservation is crucial for maintaining human health. This is due to the introduction of dangerous chemicals into the food chain, leading to the development of unexpected chronic diseases in humans and mammals. In light of this, microbial technology integration offers substantial potential for expanding the sustainable development goals.

The world's agriculture is in danger due to the growing industrialization, air and road transportation, and intensive agricultural methods used to satisfy the demands of an expanding population. The improper use of agrochemicals to increase production has lowered soil fertility, reduced biodiversity, and had a detrimental impact on the climate [1]. Consequently, there is a growing concern about the over-reliance on chemical fertilizers and pesticides, and the detrimental impacts of the random utilization of synthetic inputs on agricultural productivity and environmental quality. Over the past 20 years, food production has decreased due to the cumulative effects of environmental deterioration caused by the use of agrochemicals [2]. Hence, new approaches must be developed immediately to ensure continued development in agricultural output to counteract these adverse effects [Figure 1].

Plant growth-promoting (PGP) microbes improve agronomic efficiency and minimize the need for chemical fertilizers by lowering production costs and environmental pollution. The communications between plants and microbes in the rhizosphere are crucial in the era of sustainable crop production because they mobilize, transform, and solubilize nutrients from a limited nutrient pool [3]. This allows plants to absorb vital nutrients and reach their full genetic potential. In an integrated plant nutrition management system, the application of biological methods as a supplement to chemical fertilizers is currently growing in popularity. In this manner, employing PGP microorganisms has shown promise for developing sustainable crop production systems [4].

Figure 1 illustrates the concept of "microbial consortia," which refers to a group of different types of microorganisms working together to enhance plant growth and agricultural sustainability. This concept is adapted with permission from Negi *et al*. [1].

Conventional farming techniques that aim to increase yield pose a threat to agroecosystems. The indiscriminate utilization of chemical pesticides and fertilizers is an unpleasant experience. However, the increasing interest in PGP microorganisms for returning agro ecosystems to their natural form is inspiring. The various tasks that PGP microbes perform around plants (whether in the rhizosphere, phyllosphere, or other areas) are intricately interrelated and interdependent, making them inseparable [5]. The PGP microbes assist their host plants via direct and indirect mechanisms of plant growth promotion. The direct and indirect effects are diminished by the fact that some PGP microbes and the metabolites they generate can act in different ways under the same or different circumstances [6].

In general, PGP microbes either directly promote plant growth by facilitating the acquisition of necessary minerals through "biological N_2 fixation" a process where certain microorganisms convert atmospheric nitrogen into a form that plants can use, P solubilization, and iron sequestration by siderophores, or indirectly through induced systemic resistance, rhizosphere competition, and the biosynthesis of stress-related phytohormones such as cadaverine and jasmonic acid, or the enzyme 1-aminocyclopropane-1-carboxylate deaminase [7]. These microorganisms have been used to enhance plant growth, strengthen soil health, and increase yield. For instance, biofilm-forming microbial inoculants have demonstrated exceptional effectiveness in crop yield production, while microbial-assisted biofortifications of food crops have become a more and more common technique. In addition, by reducing greenhouse gas emissions, sequestering carbon, and other mechanisms, microbial inoculants can be useful instruments to lessen the effects of climate change [8].

In agroecosystems, the soil fertility and quality have declined due to intensive agricultural techniques and the production of exhausting crops. According to an estimate, 30% of the world's agricultural soil will be deteriorated as a result of such activities. The loss of soil productivity and structure is among the primary side effects of soil degradation. They are also believed to be a serious threat to crop production and food safety for future posterity. Restoring degraded soils sustainably could be accomplished by putting safe

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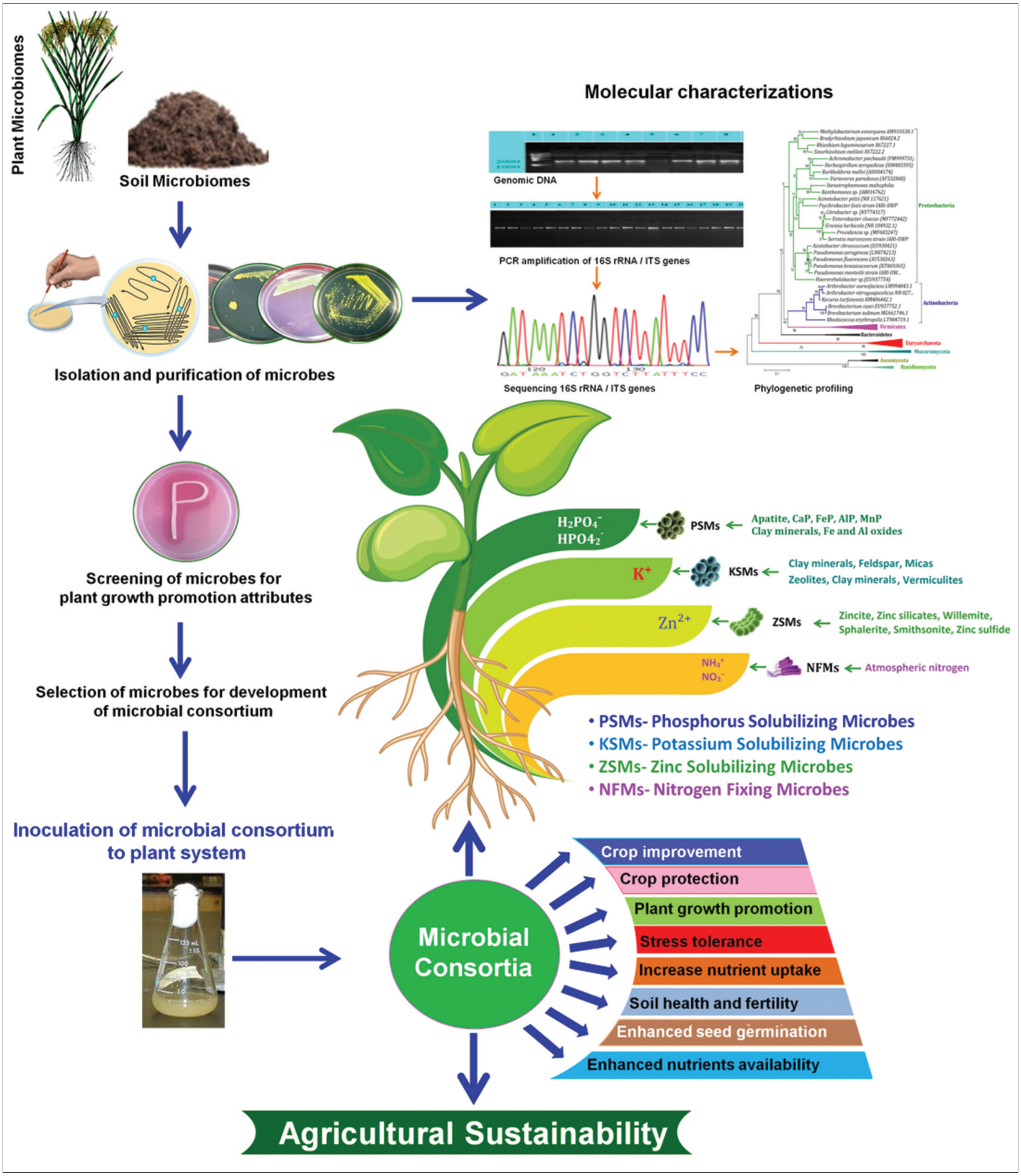

Figure 1: Microbial consortia as an untapped resource for enhancing plant growth and agricultural sustainability. Adapted with permission from Negi *et al.* [1].

and eco-friendly technology into practice [9]. Due to the vast variety of metabolic processes found in soil microbes, all key elements are cycled by their activities, which impact the capacity of soils as well as the composition and functioning of soil ecosystems to serve human needs [10]. Compared to other biological elements, microbes are an essential and fundamental component of living soil, impacting numerous biogeochemical cycles of important nutrients such as carbon, nitrogen, sulfur, and other minerals. They also play a better role in maintaining the health of the soil. In addition, they can inhibit soilborne diseases, which indirectly boost agricultural output.

Persistent, insensitive application of detrimental chemical fertilizers may disbalance the micro-ecology by destroying the beneficial soil microbes. Synthetic fertilizers must be avoided at the expense of soil biodiversity. Decreases in soil microbiota have a negative effect on nutrient cycling, which in turn reduces crop output and plant growth [11]. In addition, the subterranean biodiversity that is essential to the survival of ecosystems is diminished. Soil fertility should be restored using natural agriculture methods as effectively as possible. In light of this, organic farming is an alternative agricultural method for producing crops in a sustainable manner [12]. Global food security is at risk due to various pests and plant pathogens. To lessen the impact of plant illnesses brought on by bacterial and fungal infections, pesticide treatments are frequently utilized. Increasing food yields for the growing population is a key concern as we work toward more sustainable agriculture [13]. Biological control management is one of the most promising applications for sustainable agriculture. It is an environmentally beneficial method of controlling agricultural pests. This method employs living microorganisms to control pest populations in a systematic, reliable, and environmentally friendly way. When compared to synthetic (chemical) pest control, biocontrol agents (BCAs) are an amazing tool for safe, affordable, and sustainable pest management in developed nations, benefiting both consumers and breeders [14]. Researchers have discovered that a number of bacterial genera, such as Bacillus and Pseudomonas, exhibit antimicrobial action against a wide range of harmful bacterial and fungal plant pathogens. Several fungus genera, including *Aspergillus*, *Trichoderma*, and *Penicillium*, are frequently employed as BCAs to combat bacterial and fungal plant pathogens. A number of mycoviruses and bacteriophages have also been shown to be effective BCAs against specific plant pathogens [15].

Microbial inoculants offer more advantages than disadvantages. They are recognized for their ability to be environmentally friendly; they can improve or increase the availability of nutrients, restore soil fertility, mitigate biotic and abiotic stresses, boost soil microbial activity, break down harmful substances, encourage the colonization of mycorrhizae and other beneficial microbes, aid in the recycling of soil organic matter, boost plant defense and immunity to ward off undesired parasitic and pathogenic attacks, and perform signal transduction and plant microbe interactions [1,16]. Due to the rising expense of chemical fertilizers and societal desire for environmentally friendly solutions, the market for microbial inoculants is rising day by day [17]. Consistency, dependability, and shelf life of microbial inoculants in natural environments are the primary challenges [18]. Even if these species exhibit PGP activity, they can still be dangerous to humans; hence, due care should be taken before they are produced commercially. Pathogenic PGP microorganisms should not be used in sustainable agriculture until another investigation has been conducted. Numerous European nations, as well as the US, are reevaluating the biosafety of microbes that promote plant development [19]. The changing climate has been found to have an impact on plant-microbe interactions, but more research is required to fully understand the PGP microorganisms' potential before farmers, biofertilizer firms, and government laws accept them.

Plenty of culture-independent and dependent molecular approaches are becoming accessible and are being used to either emphasize the molecular bases of the interactions between plants and their microbiomes or to uncover the hidden diversity of microorganisms that inhabit soil as well as plant ecosystems. For the sake of plants to flourish and endure in stressful conditions, a signaling network regulates interactions between the microbiota and the plants. It is essential to comprehend this signal crosstalk to develop biotechnological techniques that maximize plant adaptation mechanisms and enhance soil microorganisms' capacity to reduce environmental stresses. Overall, scientists may assert that the use of microbial biotechnology in agriculture has led to numerous successes, but there are still many potential obstacles that must be investigated for future sustainable agricultural advancements. There is an abundance of promise to use microbes to develop a cleaner environment through ongoing innovation and interdisciplinary cooperation, which opens the door to a more sustainable future.

CONFLICTS OF INTEREST

The authors report no financial or any other conflicts of interest in this work.

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USE OF ARTIFICIAL INTELLIGENCE (AI)-ASSISTED TECHNOLOGY

The authors declare that they have not used artificial intelligence (AI)-tools for writing and editing of the manuscript, and no images were manipulated using AI.

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How to cite this article:
Yadav AN. Microbial resources: Untapped treasure for agricultural sustainability. J Appl Biol Biotech 2026;14(1):1-4. DOI: 10.7324/JABB.2026.288288ED