Journal of Applied Biology & Biotechnology Vol. 14(2), pp. i-iii, March-April, 2026
Available online at http://www.jabonline.in
DOI: 10.7324/JABB.2026.303863ed

Microbial resources: Untapped treasure for environmental sustainability

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The need for environmental sustainability to balance the resources available at present with future needs is an essential concern at the global level. Widespread human activities have resulted in significant problems, including climate change, water scarcity, land degradation, environmental pollution, and biodiversity loss. These problems have a direct effect on the quality and sustainability of the ecosystems. The utilization of beneficial microorganisms with varied ecological interactions and metabolic capabilities is gaining significant attention to address these issues. It requires additional consideration to remediate or reduce the damaging effects of human-related activities, thereby ensuring environmental sustainability. They help detoxify the environment naturally by breaking down contaminants, thus supporting crucial ecosystem functions such as reducing erosion, regulating the climate, filtering water, and improving soil quality and health. Even though advantageous microbes can address a wide range of environmental challenges, their application in a well-organized manner to resolve these challenges has yet to be realized. Additional studies are needed to better understand their ecology, gene expression, and metabolism to ensure sustainability and effectiveness on a global scale.

There is an old proverb that says when we take from nature, we have to give back. This reciprocal interaction is crucial for relationship development and sustainability. This also applies to the world of microbes and plants. The plant-microbe relationship can be utilized to receive the advantages not only for the associated microorganisms but also for the ecosystem as a whole [1]. The composition and roles of microorganisms associated with plants, as well as the genetic, biochemical, physical, and metabolic factors that shape the advantageous characteristics of plant microbiota, have been extensively researched. In order to increase agricultural productivity in the face of a variety of obstacles, such as climate change, biotic and abiotic stresses, and deteriorating soil qualities, a variety of microbial applications have been developed by utilizing the plant microbiomes [2].

The employment of microorganisms in agricultural techniques has gained a lot of attention lately, both to encourage plant development and to manage plant diseases and pests biologically. They have the ability to produce toxins that shield them against insects and diseases [3]. In recent times, they have been categorized as "jewels of the environment" due to their potential to be used in agricultural biotechnology, environmental protection measures, human and animal health applications, and the management of urban and agricultural waste. They are considered "jewels" due to their importance to a wealthy environment [4]. These microbes have a number of mechanisms that make them suitable for commercial use in the developing biotechnology to address major environmental problems. At present, beneficial microbe-based products have demonstrated exceptional performance in agro-ecosystems. Utilizing such microbes to remove pollutants, eliminate waste, and fight climate change can significantly support the continuous greener movement toward environmental sustainability in the future [5].

Since the beginning of the Green Revolution in the early 1970s, when chemical pesticides and fertilizers were introduced, agricultural productivity has significantly improved, enabling the feeding of a suffering populace. Therefore, chemical additives now dominate agricultural techniques around the world. The ecosystem, human health, and soil are all negatively impacted by the constant and impulsive use of chemicals [6]. The overuse of chemical fertilizers pollutes the soil and gradually reduces its fertility. By bio-accumulating and bio-magnifying down the food chain, excessive buildup of these chemicals in crops may have a negative impact on the health of humans and animals [7]. When plants and leaves are fertilized with inappropriate amounts of nitrogen, their nitrate content rises over permissible levels. When green vegetables are consumed with high nitrate levels, they pose a health risk to humans. The ecology and ecosystem are negatively impacted by the inconsiderate application of fertilizers that contain excessive levels of potassium and salt because they alter the pH of the soil and degrade its texture and physical makeup [8].

The process by which organic matter (OM) is broken down into distinct chemical or physical constituents is referred to as decomposition. At the macromolecular level, noticeable plant material fragments may break up into smaller particles that could be transported by water or consumed. At the molecular level, organic forms of elements, such as the carbon in a carbohydrate, oxidize to inorganic forms, like CO_2 [9]. At different stages of this process, the decomposed OM is consumed and metabolized by other organisms, which themselves will die and decompose. Therefore, decomposition is a dynamic, recursive process that completes the biogeochemical nutrient cycles through a broad range of intricate chemical, physical, and biological interactions [10]. In general, the breakdown of natural soil or additional OM releases

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vital nutrients for plant and soil communities to absorb, whereas decomposer organisms, mainly fungi and bacteria, use carbon sources that are primarily provided by primary producers, such as plants. Thus, the decomposer activity, which mineralizes organic molecules and releases vital nutrients for plants, has a close connection to the cycling of soil OM. Therefore, it is logical to assume that diversity, composition, and quantity of microorganisms in soils affect ecosystem functioning [11]. Nutrient addition can influence microbial breakdown of OM, the functional types of microorganisms, and the quality of OM. Although the involvement of bacteria and fungi in the decomposition of OM has been significantly studied, little is known about the patterns of co-occurrence and succession of these communities during the decomposition process [12].

Metals are essential to microbiological metabolic processes [13]. In contrast, higher amounts of both essential and non-essential metals can be detrimental to organisms. Heavy metals (HM) seriously damage the roots of cultivated plants and prevent the root system from growing appropriately [14]. Apart from interfering with several biological and metabolic functions, including respiration, photosynthesis, nitrogen and protein metabolism, food intake, and others, HM toxicity has become a significant problem that restricts agricultural productivity in acidic soils [15]. A decrease in biomass and diversity results from HM effects on the community of microbial cells, including changes in growth, morphology, and metabolic processes [16]. The biogeochemical cycle of hazardous metals and the cleanup of metal-contaminated settings may be significantly impacted by microbial activity. A study concluded that assessment of *Bacillus cereus* improves phytoremediation competence of *Cajanus cajan* on metal-polluted soil under controlled conditions [17]. Another study revealed that application of *Escherichia coli*, *Klebsiella*, *Staphylococcus,* and *Salmonella* enhance the growth of *Brassica juncea* L. by reducing Cr stress [18].

Plants have to constantly negotiate a changing environment comprised of barriers, including both biotic (living) and abiotic (non-living) stresses [19]. These stressors, encompassing temperature, drought, salinity, diseases, and insects, have a significant effect on plant growth and development [20]. Numerous signaling molecules coordinate a series of physiological reactions in plants that are triggered by the first sensation of stress [21]. Interestingly, there is an abundance of overlap between the signaling pathways that regulate biotic and abiotic stress responses. As an instance, the plant's hormonal salicylic acid is essential for both pathogen defence and stress tolerance [22]. Similarly, abscisic acid has long been known to play a significant role in abiotic stress responses [23].

Reactive oxygen species (ROS) are essential for fighting off infections and are involved in both abiotic stress responses. The consequences of drought, salinity, and other abiotic stresses are lessened by ROS acting as signaling molecules that cause gene expression and metabolic responses [24,25]. Various studies revealed that the application of plant growth-promoting microbes improves the growth of plants by alleviating biotic and abiotic stresses. A study documented that the application of bacterial stains identified as *Bacillus subtilis* improves the growth of rice plants by alleviating salt, arsenic, and drought stress [26]. Another study documented that *Pseudomonas chlororaphis* enhances the growth of soybean by activating Jasmonic acid (JA)-mediated resistance to promote nutrient utilization and inhibiting *Fusarium oxysporum* [27].

Microbial resources hold immense potential as sustainable solutions to some of the most pressing environmental challenges. Their unique metabolic versatility and adaptability enable them to degrade pollutants, recycle nutrients, restore ecosystems, and produce renewable bio-based products. Advances in molecular biology, omics technologies, and bioengineering are expanding the ability to identify, harness, and optimize microbial functions for environmental applications. However, realizing the full potential of these microscopic allies requires greater investment in research, improved cultivation techniques, ethical bioprospecting, and supportive policy frameworks. Integrating microbial innovations into global sustainability strategies can drive the transition toward cleaner production systems, resilient ecosystems, and a circular bioeconomy. Thus, microbes, though invisible to the naked eye, represent a powerful, untapped treasure capable of shaping a more sustainable and environmentally balanced future for the planet.

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How to cite this article:
Yadav AN. Microbial resources: Untapped treasure for environmental sustainability. J Appl Biol Biotech 2026;14(2):i-iii. DOI: 10.7324/JABB.2026.303863ed