

Advances in Agriculture-Based Technology for Sustainable Agriculture and Environment

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Dhanda, D., Saharan, B. S., Kumar, D., Kamboj, A., Goyal, Ch., Vijay, and Duhan, J. S. (2026). Advances in agriculture-based technology for sustainable agriculture and environment. *Agriculture (Poľnohospodárstvo)*, 72(1), 1–16.

In recent decades, the intensive use of synthetic pesticides and agrochemicals to maximise crop productivity has severely degraded soil physicochemical properties, contaminated water resources, caused environmental pollution, and reduced food quality and safety. In addition, heavy metals and toxicants released from agricultural activities have accumulated within agroecosystems, posing serious risks to environmental and human health. This review describes sustainable agricultural technologies and integrated management systems that can reduce chemical dependency while improving soil fertility, crop productivity, and environmental sustainability. Eco-friendly approaches, such as natural farming, biofertilisers, plant growth-promoting rhizobacteria (PGPR), biocontrol agents, bioremediation, and phytoremediation, contribute to enhanced nutrient cycling, stress tolerance, contaminant detoxification, and the restoration of ecological balance. Special emphasis is placed on how PGPR, biofertilisers, biocontrol agents, and remediation technologies can be integrated within sustainable management systems to improve agricultural resilience and soil health. Recent advances in microbial ecology, formulation technologies and integrated soil management practices are also explained to highlight their role in sustainable crop production and environmental restoration. It further demonstrates that combining these biological and remediation-based technologies can effectively mitigate the adverse impacts of conventional agricultural practices while promoting climate-resilient and resource-efficient farming systems. Overall, the study concludes that large-scale adoption of integrated sustainable agricultural strategies is essential for improving food security, reducing environmental pollution, restoring degraded ecosystems, and supporting global sustainability goals.

Keywords: sustainable agriculture & environment, bio-fertiliser, bioremediation, natural farming, agri-residues, heavy metal in agriculture, biotransformation

Ensuring a continuous and sufficient agricultural output to meet the of an exponentially growing global population is paramount to human survival. However, numerous challenges jeopardise agriculture's ability to meet current and future human needs. These challenges include climate change, soil

degradation due to erosion, rapid loss of biodiversity, compaction, salinisation, pollution, and drought. Constant increase in production costs, a decline in the number of farms, issues associated with poverty, and diminishing rural populations further compound these challenges. Notably, as traditionally practised

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in recent decades, agriculture is not only confronted with these problems but is also a primary contributor to their emergence (Singh *et al.* 2022). Moreover, excessive use of chemical fertilisers has led agroecosystems to become detached from essential plant nutrients (nitrogen and phosphorus) through internal nutrient cycling. Using huge amounts of pesticides in the field affects the soil and plants and ultimately leads to bioaccumulation. Many heavy metals produced by industries and other sectors can cause harm to animals and plants at the farm and regional levels, thereby enhancing the efficiency of fertiliser.

Nutrient recycling is enhanced through a diversified agricultural approach, in which crop production and livestock are more likely to be spatially distributed (Mohanty *et al.* 2021). Consequently, extensive mixed crop – livestock systems, especially prevalent in developing countries, have the potential to contribute significantly to future agricultural sustainability and global food security. Sustainable agricultural technology is critical to environmental preservation by promoting resource-efficient farming practices. The objective is to tackle environmental issues associated with traditional agriculture, including excessive use of synthetic chemicals, water pollution, habitat destruction, and soil degradation. These technologies use innovative methods to balance environmental preservation with agricultural productivity. First and foremost, soil health is a crucial element of environmental protection, especially through sustainable agricultural technologies. Reduced tillage, cover cropping, natural farming, and agroforestry are techniques used to improve soil quality. In addition to promoting crop production, healthy soils help maintain ecosystem stability. Encouraging the adoption of natural farming practices is another facet of sustainable technology. This entails reducing or avoiding the use of artificial fertilisers and pesticides in favour of natural techniques, including biological pest control, composting, and crop rotation (Saharan *et al.* 2023).

This review aims to critically evaluate recent advances in sustainable agricultural technologies, including biofertilisers, plant growth-promoting rhizobacteria (PGPR), biocontrol agents, bioremediation, phytoremediation, and agricultural innova-

tions, with an emphasis on their role in reducing chemical inputs and enhancing environmental sustainability. Plants also support sustainable agriculture by sustaining soil nutrient cycling. Circular agricultural principles and economic practices are further encouraged through sustainable agricultural technologies. Reusing resources and reducing agricultural waste are also integral to sustainable agriculture. By adopting practices such as closed-loop nutrient cycles, biofertilisers, biocontrol agents, natural farming, biosensing technology for pathogen detection, nano-formulation, targeted nutrient delivery, nano-enabled technologies, data-driven composting technology, and bioenergy production from agricultural residues, farmers can reduce the environmental impacts of agricultural activities. Sustainable agricultural technologies embody a comprehensive approach that prioritises environmental protection and helps achieve the sustainable development goals (SDGs). This review article shall focus on the various agricultural technologies that help sustain the environment by reducing chemical use and providing worldwide food security. These sustainable technologies help build resilient agricultural systems that benefit the environment and society by mitigating agricultural problems. Recent advances include plant transcriptomics and metabolomics for crop stress analysis (Ćavar Zeljković *et al.* 2026), analyses of the plant and seed microbiomes in agriculture (Xu *et al.* 2026; Zhang *et al.* 2026), genetically engineered microbes in agriculture (Brewer *et al.* 2026), data-driven composting technology, artificial intelligence (AI) in agriculture (Srinivasu *et al.* 2025), and plant-based nano-materials for applications in food, medicine, and environmental remediation (Guo *et al.* 2025), among others, which can be used for agricultural sustainability.

The manuscript is organised into sections covering major sustainable agricultural technologies, their mechanisms and applications, recent technological advances, and the integration of biological and ecological approaches to achieve climate-resilient and resource-efficient agriculture. Collectively, these approaches provide a framework for improving food security, restoring ecosystem health, and supporting the global sustainable development goals (SDGs).

1. Problems in Agriculture

1.1 Agri-residues

South Asia's gangetic plains (IGP), spanning India, Bangladesh, Pakistan, and Nepal, boast fertile alluvial soils, making it a highly profitable agricultural region. This area is renowned as the "Indian Green Revolution" region, often referred to as the "food bowl" or "food basket" due to its significant contribution to food production. Covering approximately 15% of India's total geographical area, the IGP states of Haryana, Punjab, Bihar, Uttar Pradesh, and West Bengal are particularly adept at implementing a double/triple crop system to ensure food security for their populations. Remarkably, they produce around 50% of the country's total food grains, feeding approximately 40% of the population. The predominant cropping system within the Indian gangetic plain (IGP) is the rice-wheat rotation, covering 53% of the total land area and approximately 42% of India's overall agricultural land. This region ranks second in global rice and wheat production, generating substantial crop residue. In addition to rice-wheat, other cropping systems, such as rice-fallow and rice-mustard-summer rice, are practised in the four zones of the IGP. However, the rice-wheat system remains predominant, encompassing 72% of the total arable land.

A large number of agro-residues are generated in India. The main agro-residue in India comes from cereal crops. This generates a large amount of agro residue. In India, major agro residues include wheat straw, sugarcane bagasse, rice straw, maize husk and other crop residues. Agro-residues represent an annually renewable and cost-effective source of natural cellulosic fibres. These residues can be classified into two distinct types. Field residues encompass materials that remain in agricultural fields once the primary crop has been harvested. Some instances of these field residues include kapok seed pods, pineapple leaves, banana pseudo-stems and leaves, cotton seed pods, cotton stalks, and cornhusks. On the other hand, process residues (such as rice straw, bagasse, wheat, and pea peel) are materials left behind after the primary crop has been processed into a valuable product. A significant residue volume is generated concurrently when the main agricultural product is isolated.

1.2 Heavy metals and pesticides in agriculture

Environmental issues have consistently attracted significant attention from the scientific community. Toxicant-induced pollution is a major environmental concern that threatens both agriculture and public health. Among the most hazardous environmental toxicants are heavy metals and pesticides. Heavy

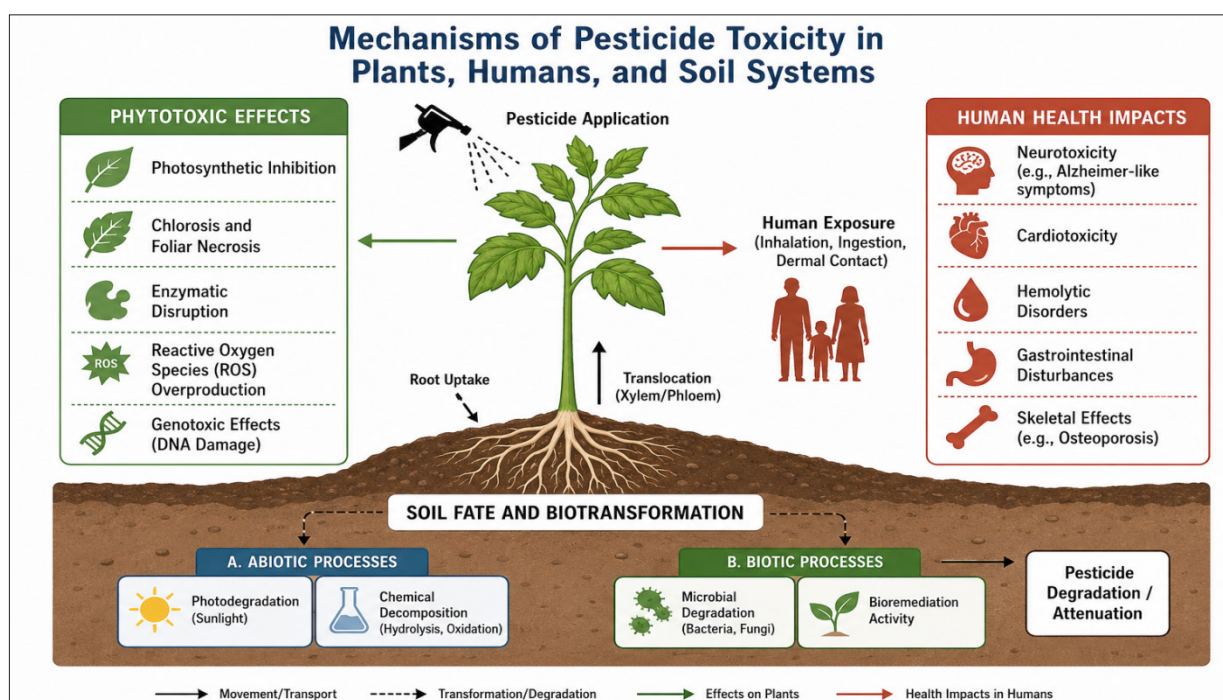


Figure 1. Mechanism of pesticide toxicity in plants, humans and soil system.

metal ions and metalloids are of particular concern as agricultural soil pollutants because of their toxicity, widespread presence, non-biodegradability, and tendency to be absorbed by crops (Figure 1). They pose a serious threat to global food safety and security.

Furthermore, the industrialisation of developing countries is increasingly contributing to the widespread contamination of agricultural land with heavy metals. Cadmium (Cd), arsenic (As), copper (Cu), mercury (Hg), lead (Pb), and chromium (Cr) are among the most commonly encountered heavy metals in soil. Approximately two million tonnes of pesticides are used globally, of which 47.5% are herbicides, 29.5% insecticides, 17.5% fungicides, and 5.5% other types of pesticides (De *et al.* 2013). The top ten countries by pesticide use include China, United States, Argentina, Thailand, Brazil, Italy, France, Canada, Japan, and India (World Atlas 2018).

Pesticides used indiscriminately can bioaccumulate within food chains and are harmful to mammals as well as other non-target organisms. In addition, they disrupt the ecological balance of local environments through both direct and indirect effects on non-target species. Pesticide residues can persist in soil, air, and plant tissues, and may even leach into water supplies. These residues are highly hazardous, as they can remain in the environment for extended periods and are associated with carcinogenic effects (Liu *et al.* 2016). Toxicants can persist within ecosystems and accumulate along the food chain, leading to increasingly evident adverse health effects. They are responsible for both acute and chronic illnesses in humans. Elevated concentrations of these toxicants can also negatively affect plant growth and development.

2. Agriculture-based Methods for Agricultural Sustainability

Sustainable agriculture promotes responsible natural resource management, waste minimisation, and efficient production systems. Environmentally friendly practices such as natural farming, crop rotation, and integrated pest management (IPM) help reduce environmental impacts and mitigate climate change. Approaches such as agroecology, conservation agriculture, and reforestation enhance carbon

sequestration, reduce greenhouse gas emissions, maintain soil fertility, and improve resilience to climate-related stresses. It also supports biodiversity conservation and ecosystem restoration through sustainable land management and agroforestry, while limiting deforestation. Achieving sustainability requires collaboration among governments, farmers, non-governmental organisations (NGOs), and other stakeholders to balance environmental, social, and economic objectives. Overall, sustainable agriculture is essential for achieving the sustainable development goals (SDGs) and for ensuring global food security, environmental protection, and societal well-being.

2.1 Plant growth-promoting rhizobacteria (PGPRs)

Plant growth-promoting rhizobacteria (PGPR) are naturally occurring soil bacteria recognised for their strong ability to colonise plant roots and their beneficial effects on plant health (Parewa *et al.* 2018). These bacteria play a vital role in several soil processes, including the decomposition of crop residues, the conversion of organic matter into essential mineral nutrients, the formation of soil organic matter, and the sequestration of nutrients. Collectively, these functions enhance soil fertility and improve crop productivity (Sharma *et al.* 2017). Plant growth promoters, whether naturally derived or synthetically produced, are widely used to enhance plant growth, development, and overall performance. They influence physiological processes within plants, resulting in improved yields, greater stress tolerance, and enhanced nutrient uptake. These promoters are particularly important in facilitating and accelerating seed germination, thereby supporting rapid crop establishment. They also help overcome seed dormancy, ensuring more uniform emergence and improved stand establishment (Mohanty *et al.* 2021). Furthermore, plant growth promoters significantly enhance root architecture and development, increasing the plant's capacity to absorb water, nutrients, and minerals. This leads to improved nutrient uptake and strengthens plant resilience to abiotic stresses such as drought, salinity, temperature extremes, and nutrient deficiencies (Naik *et al.* 2020; Maryam & Gul 2026). PGPR also stimulate shoot growth and branching, contributing to increased biomass and overall crop yield. As noted by Sabagh

et al. (2025), such growth is particularly beneficial for crops that rely on vegetative biomass, including forage crops.

In addition to stimulating vegetative growth, plant growth promoters play a key role in regulating reproductive development. They promote floral initiation, enhance fruit set, support fruit growth, and improve fruit quality by modulating the biosynthesis and balance of endogenous phytohormones, particularly auxin, cytokinin, and gibberellin, which collectively regulate flowering, cell division, cell elongation, and fruit development. Furthermore, these regulators influence assimilate partitioning and nutrient mobilisation, thereby improving fruit size, yield, and overall crop productivity. Their coordinated action also enhances reproductive efficiency by optimizing hormonal crosstalk, leading to improved flowering synchrony, fruit retention, and seed development under both normal and stress conditions (Tsukanova *et al.* 2017). Moreover, PGPR help plants cope with abiotic stresses, including extreme temperatures, salinity, heavy-metal tox-

icity, and drought. They do so by upregulating the production of antioxidants, osmoprotectants, and stress-responsive proteins, thereby improving plant survival and productivity under adverse conditions (Naik *et al.* 2020).

PGPR also enhance nutrient uptake efficiency by increasing nutrient availability and accessibility in the soil. A wide range of PGPR acts as nitrogen fixers and as solubilisers of phosphate, zinc, and potassium. Additionally, they enhance root exudation, thereby promoting beneficial microbial activity in the rhizosphere and improving nutrient mobilisation and uptake (Vejan *et al.* 2016). Given their diverse roles in promoting plant growth, development, and stress tolerance, PGPR make a significant contribution to sustainable agriculture. Through both direct and indirect mechanisms, they improve crop yields, enhance soil fertility, and support sustainable agricultural intensification, thereby contributing to economic development and food security. However, it is important to note that the effectiveness of PGPR can vary depending on crop species, soil conditions,

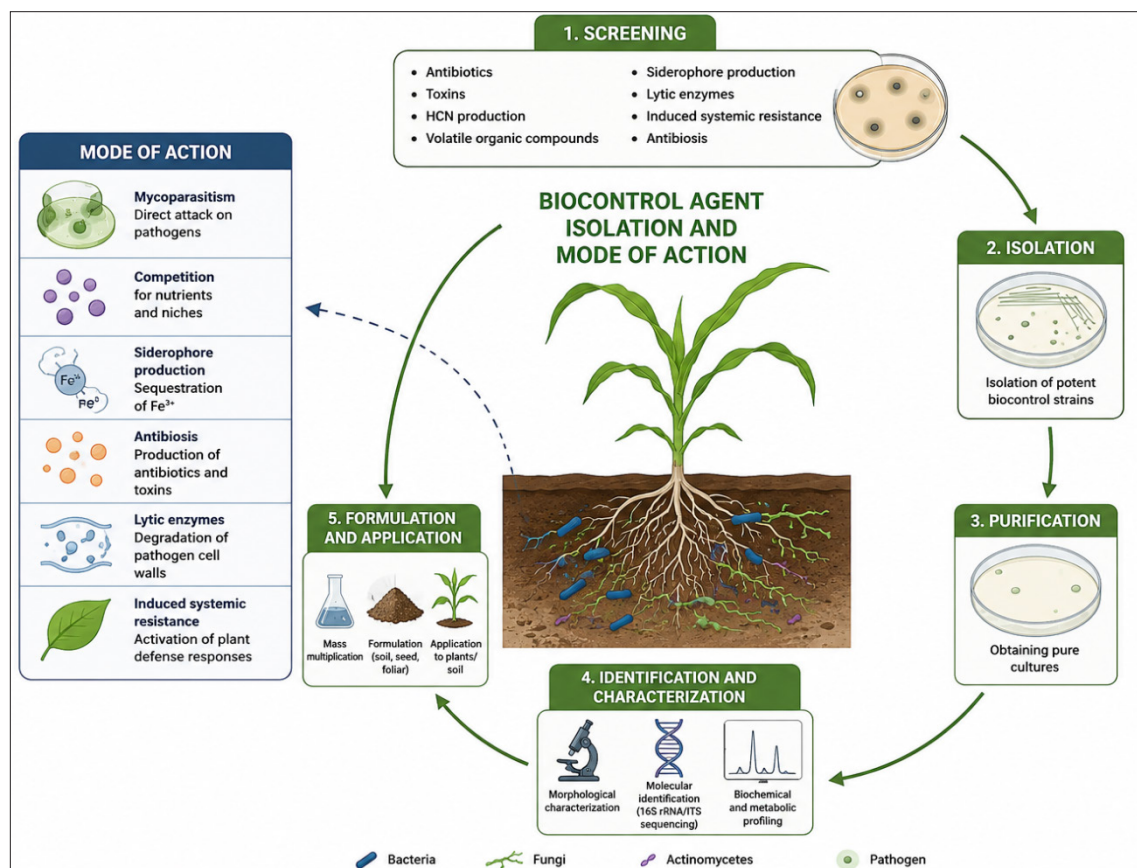


Figure 2. Bio-control agents' isolation and mode of action.

application methods, and environmental factors (Backer *et al.* 2018).

2.2 Biocontrol agent

Microorganisms known as biocontrol agents (BCAs) play a significant role in controlling phytopathogens and protecting crops from diseases such as leaf curling, root rot, wilting, and crown gall. These agents effectively regulate pest populations before they can spread disease, as they are naturally employed to combat pests without causing harm to the primary crop. Common biocontrol agents include fungi such as *Candida* spp. and *Trichoderma* spp., as well as bacteria such as *Bacillus* spp. and *Pseudomonas* spp. A key advantage of these agents is that they do not become part of the host's diet, thereby ensuring that the host remains unaffected (Savita & Sharma 2019). However, fertilisers and various pesticides are widely used to enhance crop yield and control pests. The extensive use of these chemicals has had detrimental effects on both human health and the environment. Recent studies have also explored sodium alginate-based adsorbents for enhancing pesticide removal (Sharma *et al.* 2025; Morchid *et al.* 2026).

These “natural enemies” suppress pests that harm target organisms (Heydari & Pessarakli 2010). It is well established that bacteria, fungi, and their bioactive products can be effectively utilised to control diseases, weeds, and pests, while also enhancing crop yield and supporting the health of humans and animals (Savita & Sharma 2019). Microbial biocontrol agents are widely used to protect crops from diseases and to improve both the quality and quantity of agricultural produce (Singh *et al.* 2019). Biocontrol agents (BCAs) can serve as sustainable alternatives to chemical inputs and are used as biofertilisers, biopesticides, and plant growth stimulants. Figure 2 illustrates the methods of isolation and the mechanisms underlying their action. BCAs employ a range of mechanisms to combat plant pathogens, including indirect interactions such as competition for nutrients and space, as well as the induction of plant resistance. Direct mechanisms include the production of hydrolytic enzymes, hyperparasitism, and the synthesis of antibiotics. Incorporating BCAs into integrated pest management (IPM) strategies

can significantly reduce the environmental impact associated with the use of chemical fungicides.

Further research and development are required to fully harness the potential of biocontrol agents. This includes studies on optimal formulations and dosages, as well as investigations into their interactions with the environment and native plant microflora under varying conditions. A comprehensive understanding of the mechanisms underlying their activity is essential to enhance their effectiveness as antagonistic agents. In addition, improving formulation techniques is crucial for extending the shelf life of BCAs. Microbial encapsulation is a promising approach, with alginate-based bead formulations among the most widely used methods. Biotic and abiotic factors generally influence the effectiveness of biocontrol agents. Therefore, conducting in-depth research into the environmental conditions that enable BCAs to perform optimally is essential. It is also important to understand the factors affecting rhizosphere colonisation and the interactions between BCAs and native soil microbial communities.

2.3 Bio-fertilisers

For many years, chemical fertilisers have been widely used to boost crop productivity. However, their excessive use, together with pesticides, has raised concerns about environmental and health impacts, including soil and water contamination, eutrophication, and the bioaccumulation of metal ions. These concerns have encouraged the adoption of sustainable alternatives such as biofertilisers, which enhance productivity without harmful side effects (Ghosh *et al.* 2001; Dhir 2017; Gupta *et al.* 2024).

Biofertilisers consist of beneficial microorganisms, including bacteria (*Bacillus*, *Azospirillum*, *Azotobacter*, and *Pseudomonas*), blue-green algae (BGA), and mycorrhizal fungi, which promote plant growth by fixing nitrogen and converting complex nutrients into plant-available forms. They also improve soil health by enhancing microbial diversity, moisture retention, aeration, and nutrient availability (N, P and K), thereby mimicking natural fertilisation processes (Itelima *et al.* 2018). Their effectiveness is driven by key microbial processes such as nitrogen fixation, phosphorus and zinc solubilisation, and siderophore production (Duhan & Dudeja 1998a, 1998b), along with the synthesis of

plant growth-promoting substances (Suneja *et al.* 2017; Singh *et al.* 2022). Biofertilisers are applied to seeds, soil, or roots, including foliar application, where they enhance microbial activity, improve nutrient mobilisation, and increase soil fertility, leading to better crop growth and yield (Dudeja & Dhan 2005; Mazid & Khan 2015; Gupta *et al.* 2024).

In addition, beneficial microbes enhance plant resilience to stress by regulating phytohormones and stress-related metabolites and by producing volatile organic compounds (VOCs) and secondary metabolites, including melatonin, which protect plants from pathogens (Moustafa-Farag *et al.* 2019). Plants also respond through defence mechanisms such as induced systemic resistance and the activation of enzymes (polyphenol oxidase, peroxidases and phenylalanine ammonia-lyase), thereby strengthening their ability to withstand stress (Kaur *et al.* 2022). Recent advances, including nano-formulations, green nanomaterials, and targeted nutrient delivery systems, further improve nutrient efficiency and support sustainable agriculture (Manju *et al.* 2025; Manoj *et al.* 2025; Wang *et al.* 2025; Arif *et al.* 2026).

3. Implications of Bioremediation in Agriculture

Bioremediation is a biological process that utilises microorganisms to address widespread environmental pollution (Sarkar *et al.* 2017). In the face of this challenge, microorganisms have emerged as a versatile and resilient solution due to their ability to adapt to diverse and extreme environments through their metabolic activities. Through these activities, bioremediation focuses on the breakdown, removal, transformation, immobilisation, and detoxification of pollutants and hazardous substances from the environment. Pollutants, including hydrocarbons, oils, dyes, pesticides, heavy metal ions, and other contaminants, are degraded or transformed during this process (Ullah *et al.* 2020). These changes are driven by microbial enzymatic reactions and metabolic pathways, making bioremediation an effective solution for various environmental problems. However, its efficiency depends on both biotic and abiotic factors that influence degradation rates, and their interaction significantly determines the success of the process.

On the other hand, *ex situ* bioremediation in-

volves removing and transporting contaminated soil or water to another location for treatment. These approaches include bioaugmentation, bioventing, biopiles, and bioattenuation. The selection of an appropriate method depends on the specific environmental conditions and the nature of the pollutants targeted for remediation (Tyagi & Kumar 2021). The toxic effects of heavy metals in bioremediation by microorganisms are described in Table 1. Recent advances, including biosensing technologies for pathogen detection (Shikha *et al.* 2025; Xie *et al.* 2026), RNA interference and CRISPR-based pest control strategies (Faber *et al.* 2025; Gehrke *et al.* 2025), and metal-organic framework (MOF)-based sensors (Kidānemariam *et al.* 2026), are further enhancing the efficiency and monitoring of environmental and agricultural systems.

4. Phytoremediation

Phytoremediation utilises green plants to remove, stabilise, or degrade pollutants in soil and water. Various plant species have been investigated for their capacity to accumulate and transform metal ions under different pH conditions, including both naturally occurring and genetically modified plants. Plant roots absorb metals such as cobalt (Co), copper (Cu), magnesium (Mg), and lead (Pb). While certain micronutrients (e.g., Zn, Fe, Ni, Cu, and Mn) are essential for plant metabolism, non-essential metals such as Cd, As and Hg are toxic and not required. Excess concentrations of even essential metals can disrupt physiological processes.

The selection of plant species capable of accumulating high levels of heavy metals in their biomass is critical for effective phytoremediation (Saharan *et al.* 2023). The approach includes strategies such as phytoextraction, phytostabilisation, phyto-degradation, and rhizofiltration.

5. Rhizoremediation

Rhizoremediation is a pivotal approach that targets the degradation of organic pollutants in soil adjacent to plant roots. Pilon-Smits (2005) elucidates that plant roots stimulate and enhance the catalytic activity of microorganisms, thereby facilitating pollutant degradation. Rhizoremediation offers a viable strategy for the removal of diverse organic contaminants, including petroleum hydrocarbons, by promoting their transformation into less harmful

T a b l e 1

Toxic effects of heavy metal and their bioremediation through different microorganisms

Heavy metal	Toxic Effects		Bioremediation		References
	Soil	Plants	Bacteria	Fungi	
AS	Effect minerals, organic matter, and soil microbes.	Block membrane transporters influence the generation of reactive oxygen species (ROS)	<i>Sporosarcina ginsengisoli</i> , <i>Zoogloearamigera</i>	–	Rehman <i>et al.</i> 2021
Cd	Reduce the population of microorganisms, absorb organic matter, and alter soil physicochemical characteristics.	Decrease the weight and length of the root, reduce stem conductivity, and inhibit seed germination.	<i>Zooglea</i> sp., <i>P. valderianum</i> , <i>E. cloacae</i> , <i>Ganoderma applanatum</i> , <i>D. desulfuricans</i> , <i>Citrobacter</i> sp., <i>Stereumhirsutum</i> , <i>P. ostreatus</i>	<i>R. arrhizus</i> , <i>Aspergillus</i> sp., <i>R. nigricans chrysosporium</i> , <i>Phanerochaete</i> , <i>P. chrysogenum</i> , <i>Pleurotussapidus</i>	Haider <i>et al.</i> 2021
Co	Bioavailability, effect of iron and manganese content in soil.	Pale leaves, discolored veins, leaf loss, and potential iron deficiency.	<i>P. valderianum</i> , <i>Zooglea</i> sp.	–	Mahey <i>et al.</i> 2020
Cr	Chromium hinders nutrient absorption in the soil by creating insoluble compounds.	Plant growth, nutrient absorption, and photosynthesis increase ROS, causing lipid peroxidation and changes in antioxidants, which in turn decrease plant growth, branch height, biomass, pigments, and leaf protein.	<i>Desulfovibrio vulgaris</i> , <i>Desulfovibrio fructosovorans</i> , <i>Desulfuromonas acetoxidans</i> , <i>D. desulfuricans</i> , <i>Desulfovibrio norvegicus</i>	<i>Aspergillus</i> sp., <i>Rhizopus</i> sp., <i>Aspergillus lentulus</i> , <i>Aspergillus foetidus</i> , <i>Rhizopus oligosporus</i> , <i>Termitomycesclypeatus</i>	Sharma <i>et al.</i> 2020
Cu	Change enzyme activity, decrease oxidation potential, and affect microbial communities.	Decreases the biosynthesis of chlorophyll, affects plant productivity and yield.	<i>Bacillus</i> sp., <i>Pleurotussostreatus</i> , <i>Chlorella vulgaris</i> , <i>Pseudomonas aeruginosa</i> , <i>Volvariella volvacea</i> , <i>Phormidium valderianum</i> , <i>Daedalea quercina</i> , <i>Pseudomonas stutzeri</i> , <i>Micrococcus luteus</i> , <i>Pseudomonas cepacia</i> , <i>Kocuria flava</i> , <i>Sphaerotilus natans</i> , <i>Stenotrophomonas</i> sp., <i>Citrobacter</i> sp., <i>Zooglea</i> sp., <i>Enterobacter</i> sp.	<i>R. arrhizus</i> , <i>P. spinulosum</i> , <i>Penicillium chrysogenum</i> , <i>Ganoderma lucidum</i> , <i>Aureobasidium pullulans</i> , <i>Aspergillus niger</i>	Mir <i>et al.</i> 2021
Hg	–	Suppressing crop growth or killing plants may decrease photosynthetic pigments and, antioxidant defense system.	<i>Geobacter metallireducens</i> , <i>Rhizopus arrhizus</i> , <i>C. vulgaris</i> , <i>V. volvacea</i>	<i>Candida parapsilosis</i> , <i>P. Sapidus</i>	Gworek <i>et al.</i> 2020
Ni	Effect on microorganisms in soil, enzymatic activities.	Ni toxicity decreases seed germination, root and shoot development, biomass production, and overall yield. It also induces chlorosis and necrosis, disrupts key physiological functions like photosynthesis and transpiration, and leads to oxidative damage in plants.	<i>Zooglea</i> sp., <i>P. aeruginosa</i> , <i>C. vulgaris</i> , <i>P. valderianum</i> , <i>Enterobacter cloacae</i> , <i>Desulfovibrio desulfuricans</i>	<i>Rhizopus nigricans</i> , <i>R. arrhizus</i>	Gaber <i>et al.</i> 2021
Pb	It affects soil sorption capacity, changes pH, and reduces soil fertility.	Reducing the permeability of the cell membrane and nutrient uptake damages DNA, destroys the shoot and root system, and affects enzyme activity.	<i>V. volvacea</i> , <i>Citrobacter</i> sp., <i>G. applanatum</i> , <i>D. quercina</i> , <i>Bacillus</i> sp., <i>Burkholderia</i> sp., <i>Corynebacterium glutamicum</i> , <i>C. vulgaris</i> , <i>Bacillus firmus</i> , <i>E. cloacae</i> , <i>P. aeruginosa</i> , <i>Pseudomonas putida</i>	<i>R. arrhizus</i> , <i>A. lentulus</i> , <i>P. chrysogenum</i> , <i>R. nigricans</i> , <i>P. ostreatus</i> , <i>A. niger</i>	Sarkar <i>et al.</i> 2008
Zn	Change bicarbonate ions, reduce organic matter content, and affect soil enzymatic activity and pH.	Chlorosis in younger leaves affects transportation to the leaves and hyperaccumulation in plants.	<i>Bacillus</i> sp., <i>C. vulgaris</i> , <i>D. quercina</i> , <i>P. ostreatus</i> , <i>Thiobacillus ferrooxidans</i> , <i>Acinetobacter</i> sp., <i>Streptomyces rimosus</i> , <i>A. Incharoensakdi</i> and <i>Aphanthecehalophytica</i>	<i>Trametes versicolor</i> , <i>Rhizopus arrhizus</i> , <i>Penicillium spinulosum</i>	Kaur and Garg 2021

compounds. The fundamental concept underlying rhizoremediation is that plant roots interact with indigenous soil microorganisms in contaminated environments. These interactions are initiated through the release of organic compounds from both plant roots and microorganisms, as described by Kuiper *et al.* (2004). Certain microorganisms in the rhizosphere can degrade petroleum hydrocarbons when stimulated by root exudates. The rhizosphere environment is particularly conducive to the degradation of organic pollutants. Singer (2006) explains that many organic contaminants are structurally similar to compounds exuded by plants. Due to these similarities, microorganisms in the rhizosphere are more active and abundant, enabling the degradation of contaminants even at relatively low concentrations (Yergeau *et al.* 2014).

Furthermore, the rhizosphere exhibits distinctive characteristics that enhance pollutant degradation. Kowalchuk *et al.* (2002) observed that microbial communities in the rhizosphere are more abundant and metabolically active than those in the surrounding bulk soil, largely due to root exudates. Additionally, Van Elsas and Bailey (2002) identified the rhizosphere as a hotspot for horizontal gene transfer, defined as the exchange of genetic material among microorganisms. Plasmids play a crucial role in this process, enabling microorganisms to adapt to contaminant stress and degrade complex organic compounds (Sentchilo *et al.* 2013).

Moreover, specific root exudates can enhance contaminant bioavailability by releasing them from soil organic matter, thereby improving microbial access (Gao *et al.* 2010). However, the effectiveness of rhizoremediation is largely confined to the root zone and may be limited in highly compacted or clay-rich soils, at depths beyond root penetration, or where contaminant concentrations exceed plant tolerance levels. Manschadi *et al.* (2006) noted that the success of rhizoremediation depends on selecting appropriate plant genotypes, given variations in root architecture and the quantity and composition of exudates. Rhizoremediation relies on diverse microorganisms capable of degrading and removing contaminants from the rhizosphere, including *Paenibacillus* sp., *Pseudomonas* sp., *Mycobacterium* sp., *Rhodococcus* sp., *Chryseobacterium indologenes*, *Bacillus* sp., *Staphylococcus* sp., *Bacil-*

lus circulans, *Aspergillus* sp., *Flavobacterium* sp., *Candida* sp., *Methylococcus* sp., *Trichoderma* sp., *Sphingomonas* sp., *Mesorhizobium*, *Brevundimonas* sp., *Enterobacter* sp., and *Sinorhizobium* sp. The efficiency of contaminant degradation is influenced by several factors, including soil properties, microbial composition, contaminant type and concentration, and plant species (Gao *et al.* 2010).

Many microbial species can degrade even recalcitrant compounds, such as polyaromatic hydrocarbons. Rhizoremediation is also effective for certain metallic contaminants, including arsenic (As), zinc (Zn) and cadmium (Cd), with bacteria and fungi serving as the primary agents of transformation (Lacalle *et al.* 2018). Microbially mediated processes in the rhizosphere are responsible for the removal, detoxification, or transformation of toxic metal ions, and three principal mechanisms are commonly identified for metal removal from soils (Figure 3).

The ability of biosurfactants to reduce surface and interfacial tension between fluid phases facilitates the formation of micelles that link hydrophobic and hydrophilic molecules. According to Kuiper *et al.* (2004), this mechanism enhances the solubility of hydrophobic contaminants, thereby increasing their availability for microbial degradation within the rhizosphere. In this environment, biofilms, structured assemblages of microorganisms attached to surfaces and embedded within an extracellular matrix, play a critical role. This matrix protects the microbial community and supports its stability and activity within the biofilm structure. Segura *et al.* (2009) reported that biofilms contribute significantly to the immobilisation, transformation, and degradation of contaminants during rhizoremediation.

Rhizosphere-associated microorganisms can produce a range of organic acids during growth, including citric, gluconic, lactic, malic, malonic, oxalic, and succinic acids. These compounds act as chelating agents by releasing organic anions and protons. The negatively charged anions form complexes with positively charged metal ions such as Ca^{2+} , Fe^{3+} and Al^{3+} , thereby facilitating their mobilisation from the soil matrix (Xiao *et al.* 2021; Brar *et al.* 2024). Furthermore, organic acids can serve as carbon sources and reduce soil pH, which enhances contaminant solubility and supports microbial

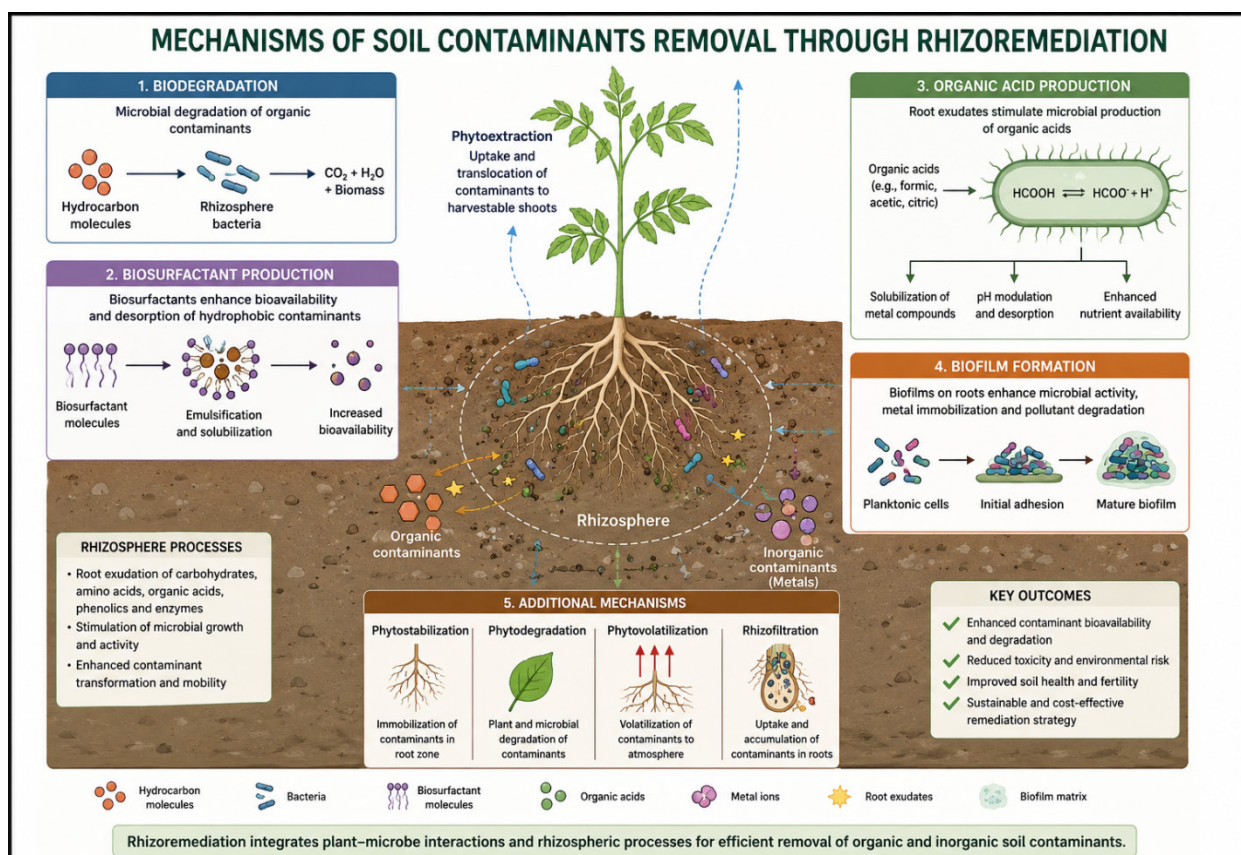


Figure 3. Mechanisms of soil contaminants removal through rhizoremediation.

activity, particularly in phosphate (P) solubilisation processes.

5.1 Biosorption

Biosorption is a biotechnological approach to remediating heavy metals (HMs) that utilises both living and non-living biomass from bacteria, fungi, and algae. This physicochemical process removes toxic substances from soil and water through mechanisms such as reduction, chelation, ion exchange, precipitation, and adsorption (Lu *et al.* 2020). Although various natural, agricultural, and industrial materials can serve as biosorbents, fungal biomass is particularly effective due to its high biosorptive capacity.

The fungal cell wall serves as the primary interface for metal binding, acting as a protective barrier and regulating the uptake of heavy metals and toxicants. It contains numerous functional groups that facilitate metal adsorption, as demonstrated in fungi such as *Penicillium chrysogenum*, *Mortierella ramanniana*, *Aspergillus niger*, *Rhizopus sexualis*, *Zygorhynchus heterogamus*, *R. stolonifer*, *Z. mo-*

elleri, *Trichoderma viride*, and *Mucor racemosus*. However, biosorption efficiency is pH-dependent; at pH 3.0, biosorption of Ni, Cu and Zn is minimal, likely due to competition between metal cations and hydronium ions for binding sites, as observed in *Aspergillus niger* (Legorreta-Castañeda *et al.* 2020). In contrast, neutral to alkaline pH conditions (7.0–9.0) significantly enhance biosorption efficiency, as reported for Fe, Ni and Zn using *Aspergillus japonicus* and *Phanerochaete chrysosporium* (Espinosa-Ortiz *et al.* 2016). Furthermore, acid treatment has been shown to influence arsenic [As(V)] biosorption, with *Neosartorya fischeri* demonstrating enhanced removal, whereas *Aspergillus fumigatus* exhibited reduced biosorption capacity under similar conditions (Urik & Matus 2018).

5.2 Biotransformation

Biotransformation involves the conversion of metals, metalloids, and radionuclides by microorganisms through modifications of the microenvironment surrounding the cell. This process includes reduction, oxidation, and catalytic reactions, which

influence the mobility, solubility, and toxicity of metal species, as well as methylation and demethylation reactions (Singh 2006; Gadd *et al.* 2014). These transformations can lead to volatilisation and detoxification of metals, thereby reducing their environmental impact. Additionally, metal ions are transported within fungal systems via cytoplasmic vacuoles and vesicles associated with the mycelium. Yeasts and wood-rot fungi are particularly noted for their ability to biotransform a wide range of organic xenobiotics, including chlorinated phenols, phenyl alkanes, dibenzofurans, ethers, ethylated benzenes, dioxins, polycyclic aromatic hydrocarbons, and halogenated compounds (Schlüter & Schauer 2017). However, it is important to recognise that these transformations may produce intermediate compounds with varying properties, necessitating careful risk assessment of the resulting products.

5.3 Bioprecipitation

Bioprecipitation contributes to the transformation of environmental contaminants through metabolically mediated processes occurring in the vicinity of fungal cells. Under oxygenated conditions, microorganisms transfer electrons from donor molecules to oxygen, facilitating aerobic metabolism (Remoudaki *et al.* 2007). This process leads to the mineralisation of organic carbon to carbon dioxide (CO₂) and the reduction of oxygen to water, resulting in an increase in pH within the cellular microenvironment. Consequently, bicarbonate ions are generated, promoting the precipitation of heavy metals and toxicants in the form of carbonates and metal hydroxides. This mechanism illustrates the interaction between fungal metabolic activity and environmental conditions, ultimately influencing the fate and speciation of metal ions near microbial cells.

6. Natural Farming

Natural farming, also referred to as farming with nature, is an agricultural approach that emphasises harmonious interaction with natural ecosystems. It minimises the use of synthetic chemicals, pesticides, and fertilisers, thereby enhancing soil fertility, biodiversity, and overall ecological balance while maintaining productivity (Saharan *et al.* 2023). Natural farming represents a revival of traditional agricultural practices, offering a self-sustaining solution to modern farming challenges. In this system, agri-

cultural activities are conducted without reliance on external inputs such as chemical fertilisers and pesticides, resulting in minimal or zero input costs (Table 2) and incorporating innovative organic farming methods (Meshram *et al.* 2026).

Instead, natural farming utilises locally available biological resources, including plant residues, cow dung, jaggery, and urine, to enhance soil health (Bharucha *et al.* 2020). Preparations such as Jeevamrit, Beejamrit and Panchgavya are widely used to stimulate microbial populations and increase earthworm activity in the soil. These inputs improve nutrient availability, microbial antagonistic activity, and plant defences, ultimately enhancing crop productivity (Ray *et al.* 2025). Increased microbial diversity strengthens the resilience and stability of the soil ecosystem, while diverse communities of fungi and bacteria facilitate the decomposition of organic matter and nutrient cycling, thereby improving soil fertility and crop yield. Additional natural farming practices, including mulching, wapsa, and crop rotation, further conserve soil moisture, suppress weeds, and prevent soil degradation, collectively supporting sustainable agricultural productivity.

CONCLUSIONS

Ecological technologies are increasingly recognised as cornerstone strategies for sustainable agriculture and environmental restoration in response to escalating climate change, environmental pollution, soil degradation, biodiversity loss, and global food security challenges. Nature-based solutions such as bioremediation, phytoremediation, mycoremediation, and rhizoremediation have demonstrated substantial potential to restore contaminated soils and ecosystems through the detoxification capacity of plant systems, fungi, and plant-microbe interactions. These environmentally benign and cost-effective approaches not only remove pollutants but also improve nutrient cycling, enhance soil structure, promote microbial diversity, and strengthen ecosystem resilience. However, their effectiveness is strongly influenced by site-specific factors such as soil type, contamination level, climatic conditions, and crop systems, highlighting the importance of integrated, location-specific management strategies.

Simultaneously, natural farming approaches sup-

T a b l e 2

Different methods used in natural farming/ conservation biology and their roles in plant growth and development

Plant Nutrition			References
Method(s)	Preparation/composition/ ingredients	Purpose/benefit(s)	
<i>Jeevamrit</i>	Cow urine (5 – 10 L), cow dung (20 kg), jaggery (20 kg), flour (2 kg)	A source of nutrients while also functioning as a catalyst to enhance the microbial activity in the soil and stimulate earthworm activity. Additionally, it contributes to the prevention of fungal and bacterial diseases.	Saharan <i>et al.</i> 2023; Via Campesina 2016
<i>Ghanjeevamrit</i>	Cow dung (200 kg) Jeevamrutham (20 L)	Nutrient provider, increase microbial activity.	Nagar <i>et al.</i> 2023
<i>Beejamrit</i>	Cow urine (5 L), cow dung (5 kg), lime (50 g), soil	For seed treatment designed to safeguard young roots against fungal, soil-borne, and seed-borne diseases.	Nagar <i>et al.</i> 2023
<i>Neemaster</i>	Cow dung (5 kg), cow urine (5 L), neem leaves and pulp (5 kg)	Employed for the management of sucking pests and borers (fruit and pod).	Charapale <i>et al.</i> 2021
<i>Agniaster</i>	10 L of local cow urine 1 kg tobacco 500 g of local garlic 500 g of green chilli 5 kg neem leaves pulp (crushed in urine).	Efficacy in combating pests such as stem borers, leaf rollers, pod borers, and fruit borers.	Charapale <i>et al.</i> 2021
<i>Brahmaster</i>	Cow urine, neem, guava, pomegranate, papaya, lantern camellia, white datura, and custard apple leaves	For the regulation of sucking pests.	Saharan <i>et al.</i> 2023; Charapale <i>et al.</i> 2021
Plant Protection			
Chemical(s)	Plant name(s)	Benefits/uses	
Pyrethrin	<i>Chrysanthemum cinerariifolium</i>	Insecticides	Shaan <i>et al.</i> 2005
Camphor	<i>Cinnamomum camphora</i>	Insect repellent	Shaan <i>et al.</i> 2005
Leaves and seeds	<i>Azadirachta indica</i>	Anti-microbial activity	Shaan <i>et al.</i> 2005
Strychnine	<i>Strychnos nuxvomica</i>	Rats and other animals	Annison <i>et al.</i> 1960
Nicotine	<i>Nicotiana glauca</i>	Insecticides	Sanchez-Hernandez 2019
Rotenone	<i>Derris elliptica</i>	Kill caterpillars and other insects	Sanchez-Hernandez 2019
Veratridine	<i>Veratrum album</i>	Insecticides	Shaan <i>et al.</i> 2005
Coumarin	<i>Dipteryx odorata</i>	Fungicides	Sanchez-Hernandez 2019
Potassium fluoroacetate	<i>Dichapetalum cymosum</i>	Kill rats	Annison <i>et al.</i> 1960
Agronomical practices/strategies/phenomena			
Mulching	Straw mulch, leaf mulch, soil mulch	Moisture retention, control weed growth	Via Campesina 2016; Saharan <i>et al.</i> 2023; Saharan <i>et al.</i> 2021
Wapsa	Reduction in irrigation, or low irrigation	Maintain moisture content	Via Campesina 2016
Intercropping	Cultivation of two or more crops simultaneously on the same field, mainly in rows	Increase soil fertility, pest control, and weed control.	Via Campesina 2016; Saharan <i>et al.</i> 2021
Mix cropping	Growing two or more crops together on the same piece of land	Increased productivity, pest control, and disease control	Via Campesina 2016; Saharan <i>et al.</i> 2023
Crop rotation	Growing different crops in the same area across several seasons	Results in an increase in organic content in the soil, refines soil structure, mitigates soil degradation, and has the potential to yield increased crop production and enhanced farm profitability over the long term.	Via Campesina, 2016; Saharan <i>et al.</i> 2023

ported by biofertilisers, plant growth-promoting rhizobacteria (PGPR), and biocontrol agents are providing sustainable alternatives to chemical-intensive agricultural practices. These biological inputs improve nutrient availability, stimulate plant growth, enhance tolerance to abiotic and biotic stresses, suppress phytopathogens and pests, and maintain rhizosphere health while reducing dependence on synthetic fertilisers and pesticides. The integration of remediation technologies with biological soil management therefore represents a holistic framework for improving agricultural productivity alongside environmental restoration. Such integrated approaches may be particularly valuable in small-scale farming systems, intensive agricultural regions, and degraded or contaminated soils, where sustainable resource management is essential.

Recent advances in microbial ecology, molecular biology, nano-formulation technologies, biosensing systems, artificial intelligence-assisted agriculture, precision nutrient delivery, and microbial consortia development are further improving the stability, efficiency, and field applicability of ecological technologies. Despite these advances, several constraints continue to limit large-scale implementation, including high initial costs, limited availability of high-quality microbial inoculants, inconsistent field performance, formulation instability, seasonal variability, regulatory limitations, and the need for specialised application methods. In addition, while technologies such as biofertilisers, PGPR-based products, and certain biocontrol agents are already commercially applicable in many agricultural systems, advanced remediation technologies, engineered microbial systems, and several nano-enabled approaches remain largely at the research and developmental stage.

Overall, ecological technologies grounded in biological diversity and natural processes offer considerable promise for restoring environmental health while ensuring sustainable agricultural productivity and long-term food security. Future efforts should focus on integrated, systems-based agricultural management approaches that combine remediation technologies, soil health management, crop productivity enhancement, and climate-resilient practices. Strengthening collaboration among

researchers, farmers, industry, agricultural advisers, and policymakers will be essential to improving technology transfer, establishing supportive regulatory frameworks, increasing farmers' awareness, and accelerating the adoption of sustainable agricultural technologies aligned with global sustainability goals and socio-economic development.

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Received: February 15, 2026

Accepted: June 18, 2026