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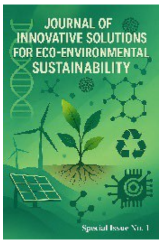

Review Article

Utilizing Green technology for a Sustainable Future

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ABSTRACT

The 2030 Agenda for Sustainable Development underscores the urgent need for environmentally sustainable and resource-efficient technologies to address global challenges related to food security, energy demand, environmental degradation, and climate change. This review aims to critically evaluate the role of sustainable biotechnology as a green technological approach for advancing the United Nations Sustainable Development Goals (SDGs). The literature for this review was systematically selected from peer-reviewed research articles, review papers, and authoritative reports indexed in major scientific databases including Scopus, Web of Science, PubMed, and Google Scholar. Studies were screened based on relevance, scientific rigor, and their contribution to sustainability-oriented biotechnological applications across agriculture, energy, environmental remediation, and industrial processes. Key findings highlight those biotechnological interventions such as biofuels, biofertilizers, biopesticides, bioplastics, bioenzymes, bioremediation, and waste valorization offer effective alternatives to conventional chemical-based technologies. These approaches contribute to reduced environmental pollution, enhanced resource efficiency, improved soil and crop productivity, waste minimization, and lower greenhouse gas emissions. Collectively, these innovations support multiple SDGs, including zero hunger, affordable and clean energy, responsible consumption and production, climate action, and ecosystem conservation. Despite notable progress, significant gaps remain in terms of large-scale implementation, cost competitiveness, regulatory standardization, lifecycle sustainability assessments, and public acceptance. Future research should focus on interdisciplinary approaches, integration of biotechnology with circular economy models, development of standardized performance metrics, and supportive policy frameworks to facilitate commercialization and adoption. Overall, sustainable biotechnology represents a promising pathway for achieving long-term environmental sustainability and socio-economic resilience.

1. Introduction

Biotechnology is biology-based technology that develops products and technologies that enhance our lives and the health of our planet by utilising cellular and biomolecular processes [1]. For more than 6,000 years, humans have used the biological processes of microorganisms to preserve dairy products and make nutritious foods like cheese and bread. Utilising biological processes like fermentation and biocatalysts like microbes or microbial enzymes to create valuable goods is the foundation of biotechnology [2]. Biotechnologies improve the efficiency of several manufacturing processes and optimise the phases of chemical production processes by 80% or more. Greenhouse gas emissions are cut by at least 52% when biofuels are used.

In addition to ensuring their sustainable usage, biotechnology aids in the reduction of waste production and water consumption [3]. The production of food is posing an increasing challenge to the world society. With the aid of biotechnology, it can be achieved to increase crop resistance to pests and herbicides, encourage the adoption of more ecologically friendly farming methods, increase crop yields at a lower cost, and limit the quantity of agricultural chemicals that are required to grow crops and, consequently, their release into the environment.

Globally, the demand for primary healthcare is always rising.

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By lowering the prevalence of infectious diseases, saving the lives of millions of children, providing individualised therapy to reduce health risks and side effects, and developing more precise disease detection tools, biotechnology, with its unique set of tools and techniques, contributes to global healing[4]. Patients have access to over 250 biotech healthcare items and vaccinations, many of which are intended to cure diseases that were previously incurable. The use of biotechnology is a measure of a nation's degree of progress. Biotechnological fields are actively encouraged and developed in industrialised nations through the use of contemporary research techniques like genetic engineering and molecular biology.

2. Bioplastics

Plastics are synthetic or semi-synthetic organic polymers that are lightweight, durable, versatile, and economically attractive, making them indispensable in modern society. Approximately 99% of conventional plastics are derived from non-renewable fossil resources such as petroleum, natural gas, and coal. Consequently, the plastics sector accounts for nearly 20% of global petroleum consumption [5]. In Europe, the major plastic-consuming sectors include packaging (≈40%), construction (≈20%), textiles (≈15%), automotive applications (≈10%), and consumer products (≈10%), with demand expected to rise further due to urbanisation and industrial growth [6].

Despite their functional advantages, plastics pose severe environmental challenges due to their persistence and fragmentation into smaller particles. Mechanical abrasion, UV radiation, and chemical weathering lead to the formation of plastic debris classified as macroplastics (>25 mm), mesoplastics (5–25 mm), microplastics (<5 mm), and nanoplastics ($<10^{-4}$ mm) [7]. These particles accumulate predominantly in marine ecosystems, threatening aquatic organisms, entering food webs, and posing potential risks to human health [8]. Inefficient waste management and low recycling rates further exacerbate plastic pollution, raising concerns regarding the long-term environmental resilience of polymeric materials [9].

In this context, bioplastics have emerged as a sustainable alternative. Bioplastics are materials derived partly or wholly from renewable biomass sources such as vegetable oils, starch, cellulose, agricultural residues, wood chips, and reprocessed food waste. They are broadly classified into bio-based, biodegradable, or both, depending on their origin and end-of-life behaviour [10]. Biodegradable bioplastics undergo microbial degradation under specific conditions, yielding CO_2 and H_2O under aerobic conditions, and CO_2 and CH_4 under anaerobic environments. However, biodegradation efficiency strongly depends on temperature, moisture, oxygen availability, and microbial activity, meaning that many bioplastics degrade effectively only in industrial composting facilities rather than natural soil or marine environments [11,12].

From a lifecycle assessment (LCA) perspective, bioplastics generally demonstrate lower greenhouse gas emissions and fossil energy demand during production compared to conventional plastics, particularly when waste biomass is used as feedstock [13]. Nevertheless, environmental trade-offs remain. Land-use change, fertiliser use, water consumption, and competition with food crops can offset sustainability benefits if first-generation biomass resources are employed [14]. Additionally, methane emissions during anaerobic degradation and incomplete mineralisation in natural ecosystems raise concerns regarding their real-world environmental performance.

Several commercially important bioplastics include poly(3-hydroxybutyrate) (PHB), poly(ε-caprolactone) (PCL), poly(butylene succinate) (PBS), poly(lactic acid) (PLA), and poly(ethylene succinate) (PES) [15]. Among these, PLA and polyhydroxyalkanoates (PHAs) dominate the global bioplastics market due to their favourable mechanical properties, compostability certifications, and expanding industrial acceptance. According to recent estimates, global bioplastics production capacity reached approximately 2.2–2.5 million tonnes in 2023, representing less than 1% of total plastics production but growing at an annual rate exceeding 15%, driven largely by packaging, agriculture, and textile applications [16].

PHAs are a family of aliphatic polyesters synthesised by microbial fermentation of renewable substrates and are valued for their biocompatibility, non-toxicity, and full biodegradability in soil, freshwater, and marine environments [17]. These polymers can be produced using agricultural residues, green waste, wastewater sludge, and non-food biomass, reducing reliance on edible feedstocks [15]. Their physicochemical properties—such as crystallinity, flexibility, and thermal behaviour—vary with monomer composition and fermentation conditions, enabling tailored applications in packaging, fibres, and biomedical implants [18].

PHAs are classified into short-chain-length (3–5 carbon atoms), medium-chain-length (6–14 carbon atoms), and long-chain-length (>14 carbon atoms) polymers (Muniyandi et al., 2020). Among them, PHB is the most extensively studied. PHB exhibits thermoplastic properties comparable to fossil-based polypropylene, including high stiffness, crystallinity (60–80%), and a melting temperature around 180 °C [17]. However, its inherent brittleness and narrow processing window limit large-scale adoption, prompting the development of copolymers such as poly(3-hydroxybutyrate-co-3-hydroxyvalerate) [P(3HB-co-HV)] to improve flexibility and toughness [19].

PLA is another prominent bioplastic, produced via ring-opening polymerisation of lactide derived from lactic acid obtained through microbial fermentation of renewable carbohydrates [20]. Owing to its transparency, mechanical strength, processability, and non-toxicity, PLA has gained widespread commercial acceptance, particularly in food packaging, disposable products, and biomedical devices [21]. However, PLA biodegrades efficiently only under controlled industrial composting conditions (≥58 °C), limiting its environmental benefits when disposed of improperly.

Despite rapid market growth, bioplastics face several challenges, including high production costs, limited composting infrastructure, contamination of conventional recycling streams, and inconsistent biodegradation standards across regions [22]. Addressing these challenges through improved feedstock selection, advanced bioprocessing, robust LCA frameworks, and supportive policy mechanisms is essential for maximising the sustainability potential of bioplastics.

Bioplastics are increasingly recognized as sustainable alternatives to conventional petroleum-based plastics; however, their environmental benefits are highly dependent on life cycle performance, degradation behavior, and end-of-life management. Life cycle assessment (LCA) studies show that bioplastics such as polylactic acid (PLA) and polyhydroxyalkanoates (PHAs can reduce greenhouse gas emissions and fossil energy use by approximately 20–70%, provided that renewable feedstocks and optimized production pathways are employed [23, 22]. Nevertheless, upstream impacts related to land use change, water consumption, fertilizer application, and competition with food crops may offset these benefits, highlighting critical environmental trade-offs associated with first-generation biomass feedstocks [24].

The biodegradation behavior of bioplastics varies significantly across material types and environmental conditions. PHAs demonstrate complete biodegradation in soil, freshwater, marine, and composting environments, whereas PLA typically requires industrial composting conditions (≥58 °C, controlled humidity, and active microbial communities) for efficient degradation [23]. In natural environments, incomplete degradation of certain biodegradable plastics may result in secondary microplastic formation, raising ecological concerns .

From a global perspective, bioplastics production capacity reached approximately 2.2–2.5 million tonnes in 2023, accounting for less than 1% of total plastics production, yet exhibiting annual growth rates exceeding 15%, driven primarily by packaging, agriculture, and consumer goods sectors [16]. Despite favorable market trends, challenges such as high production costs, limited industrial composting infrastructure, recycling stream contamination, and inconsistent biodegradability standards continue to constrain large-scale adoption, underscoring the need for harmonized policies, improved waste management systems, and robust LCA-based decision frameworks.

3. Bioenzymes

Bioenzymes are environmentally benign biocatalytic formulations primarily derived from the anaerobic fermentation of fruit and vegetable peels, which are otherwise discarded as organic waste. Because their raw materials are biodegradable and renewable, bioenzymes contribute to waste reduction and sustainable resource utilisation. They are non-toxic, non-corrosive, non-hazardous, and safe for both human use and the environment. Typically, bioenzymes are produced by fermenting fruit and vegetable residues with water and carbohydrate sources such as jaggery, molasses, or brown sugar, often aided by naturally occurring yeast and bacteria [25, 26]. The concept of bioenzymes was pioneered by Dr. Rosukon Poompanvong in Thailand, and these products are also referred to as eco-enzymes, garbage enzymes, terrazyme, fruit enzymes, or flower enzymes [27, 28].

Chemically, bioenzymes are complex mixtures of proteins (enzymes), carbohydrates, organic acids, metabolites, and secondary microbial products formed during fermentation. Their catalytic efficiency arises from enzyme-mediated biochemical reactions that significantly accelerate substrate breakdown under mild conditions. The major enzymatic components typically include proteases, lipases, amylases, and cellulases, which act synergistically to degrade proteins, fats, starches, and cellulose, respectively [25].

Mechanism of Enzymatic Action

Bioenzymes function through highly specific enzyme–substrate interactions. Enzymes bind substrates at their active sites to form enzyme–substrate complexes, lowering activation energy and accelerating reaction rates. Proteases hydrolyse peptide bonds in proteinaceous stains, lipases cleave ester bonds in fats and oils, amylases break α-1,4-glycosidic bonds in starch, and cellulases degrade cellulose-based residues. These reactions typically occur at near-neutral pH (6–8) and moderate temperatures, making bioenzymes effective under low-energy conditions [29]. The formation of smaller, water-soluble molecules facilitates easy removal of soils without aggressive mechanical action.

Compared to conventional synthetic chemical detergents, bioenzymes offer several advantages. Chemical cleaners often rely on harsh surfactants, oxidising agents, and alkaline compounds that can cause skin irritation, equipment corrosion, and environmental toxicity. In contrast, enzymatic cleaners operate effectively at lower temperatures and lower concentrations, reducing energy consumption and chemical load [30]. Enzymatic detergents also generate fewer harmful byproducts and exhibit superior biodegradability. Life cycle assessments have shown that enzymatic formulations can reduce greenhouse gas emissions by up to 40% compared to traditional chemical detergents, largely due to reduced heating requirements during washing processes [31].

Bioenzymes find extensive applications in household cleaning, agriculture, wastewater treatment, healthcare sanitation, and textile processing. Enzymatic cleaners are widely used in sterile processing and endoscopy departments for cleaning medical instruments, as they efficiently remove organic residues from complex surfaces. In domestic settings, bioenzymes serve as surface cleaners, carpet stain removers, odour eliminators, and toilet cleansers, effectively penetrating porous surfaces such as grout to remove embedded soils. Their effectiveness at lower washing temperatures has contributed to enzymatic detergents capturing more than 50% of the global laundry detergent market, significantly reducing energy demand associated with laundering [29].

Proteolytic enzymes are among the most commercially valuable bioenzymes and are ubiquitous across biological systems. Protease-producing microorganisms are being extensively explored to produce industrial-grade enzymes for applications such as stain removal, leather processing, food modification, and pharmaceutical manufacturing [32]. Similarly, β-galactosidase-producing microorganisms isolated from fermented millet mixtures have demonstrated potential for producing lactose-free milk and improving bakery products by enhancing dough properties [33, 34].

Despite their advantages, large-scale bioenzyme production faces several challenges. Variability in raw material composition, extended fermentation times, enzyme stability, and inconsistent enzyme activity can affect product quality and scalability. Additionally, downstream processing, storage stability, and standardisation remain technical hurdles for industrial adoption [35]. Regulatory approvals, shelf-life limitations, and consumer awareness further influence market penetration. Advances in microbial strain improvement, enzyme immobilisation, controlled fermentation technologies, and formulation stabilisation are critical to overcoming these challenges and enabling wider commercial deployment.

At the molecular level, enzymatic action involves the formation of an enzyme–substrate complex at a highly specific active site, where non-covalent interactions such as hydrogen bonding, ionic forces, and hydrophobic interactions stabilize the transition state and lower the activation energy of reactions [36,37]. Enzymes employ mechanisms such as acid–base catalysis, covalent catalysis, and metal-ion-assisted catalysis, allowing reactions to proceed rapidly under mild temperature and pH conditions with minimal by-product formation [38].

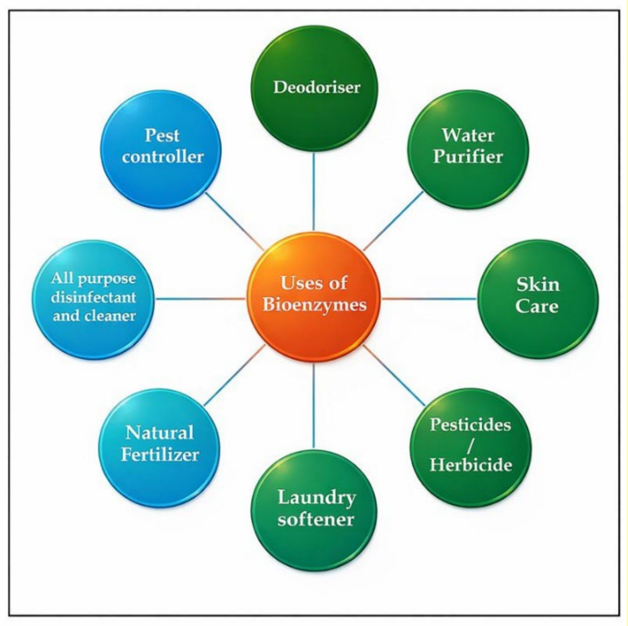

Figure 1. Different uses of Bioenzymes

Compared to conventional synthetic chemical catalysts, bioenzymes offer significant advantages in terms of energy efficiency, selectivity, and environmental impact. Enzymatic processes typically operate at ambient temperatures and atmospheric pressure, reducing energy consumption and greenhouse gas emissions, while their high chemo-, regio-, and stereoselectivity minimizes unwanted side reactions and downstream purification requirement [37]. In contrast, synthetic chemical catalysts often rely on high temperatures, extreme pH, toxic solvents, or heavy metals, contributing to increased waste generation and ecological burden. Consequently, bioenzymes have increasingly replaced synthetic chemicals in industries such as detergents, food processing, textiles, pharmaceuticals, biofuels, and wastewater treatment [38].

Despite these advantages, the large-scale production and industrial deployment of bioenzymes remain challenging. High production costs associated with microbial fermentation, downstream purification, and formulation significantly affect economic feasibility [39]. Additionally, enzyme instability under harsh industrial conditions—such as high temperatures, extreme pH, organic solvents, and shear stress—limits operational lifespan and reusability, while scale-up often results in reduced yields due to mass transfer limitations and inconsistent expression levels [40]. To overcome these barriers, current research focuses on protein engineering, enzyme immobilization, metabolic pathway optimization, and the use of low-cost substrates such as agro-industrial waste, although these strategies can introduce additional complexity and cost [38]. Overall, bioenzymes remain a cornerstone of sustainable biotechnology, provided that technological and economic constraints are effectively addressed.

4. Biofuels

Global energy demand continues to rise rapidly due to population growth, urbanisation, and industrial expansion. Fossil fuels have historically met a substantial portion of this demand; however, their continued exploitation has led to severe resource depletion, environmental degradation, and climate change. Combustion of fossil fuels releases large quantities of carbon dioxide (CO_2), a major greenhouse gas responsible for global warming and ecological imbalance. Consequently, the development of affordable, renewable, and environmentally sustainable energy alternatives has become a global priority [41,43].

Biofuels have emerged as a promising renewable energy source due to their potential to reduce greenhouse gas emissions and dependence on fossil fuels. Biofuels are energy-rich solid, liquid, or gaseous fuels derived directly from biological processes or through chemical conversion of biomass originating from living or previously living organisms. Most biofuels are produced from photosynthetic organisms such as terrestrial plants, algae, cyanobacteria, and photosynthetic bacteria. These bioenergy products can be further transformed using thermochemical, physical, or biological processes to improve energy density and usability [42].

Biofuels are broadly classified into primary and secondary biofuels. Primary biofuels are obtained through the direct combustion of biomass such as firewood, crop residues, and animal waste. Secondary biofuels are produced indirectly through processing and are categorised into three generations. First-generation biofuels, including bioethanol from starch-rich crops (e.g., corn and sugarcane) and biodiesel from animal fats or used cooking oil, have achieved commercial success but face sustainability concerns. These include competition with food supplies, high water usage, and land-use change, contributing to the ongoing “food versus fuel” debate [44].

Second-generation biofuels utilise non-food lignocellulosic biomass such as agricultural residues, forestry waste, and dedicated energy crops. While these biofuels reduce competition with food resources, challenges such as costly pretreatment, enzyme inefficiency, and low conversion yields limit their large-scale deployment [45]. Third-generation biofuels, derived primarily from microalgae, cyanobacteria, and other microorganisms, are considered the most promising due to their high growth rates, superior lipid productivity, and ability to grow on non-arable land using saline or wastewater. Additionally, algal biofuels offer the potential for carbon capture and wastewater treatment, enhancing their sustainability profile [37].

Waste-to-biofuel approaches further strengthen the sustainability of bioenergy systems. Fruit and vegetable waste generated in households and markets represents an abundant, low-cost feedstock for bioethanol production. Studies have demonstrated successful ethanol production from wastes such as pineapple peels, sweet potato residues, jackfruit waste, and water chestnut biomass, transforming organic waste into valuable bioenergy while reducing landfill burden [46]. Such circular bioeconomy strategies align with sustainable waste management and energy recovery goals.

In addition to liquid biofuels, microbial fuel cell (MFC) technology has gained attention as an innovative approach for direct electricity generation using microbial metabolism. MFCs exploit electrochemically active microorganisms to convert chemical energy stored in organic substrates into electrical energy. This technology is regarded as clean, renewable, and environmentally friendly, as it can simultaneously generate electricity and treat wastewater with minimal harmful byproducts (Logan, 2004; Venkata Mohan et al., 2008). Although power densities remain relatively low, recent advances in electrode materials, reactor design, and microbial consortia have significantly improved MFC performance, highlighting their potential for decentralised energy generation and sustainable wastewater treatment [47].

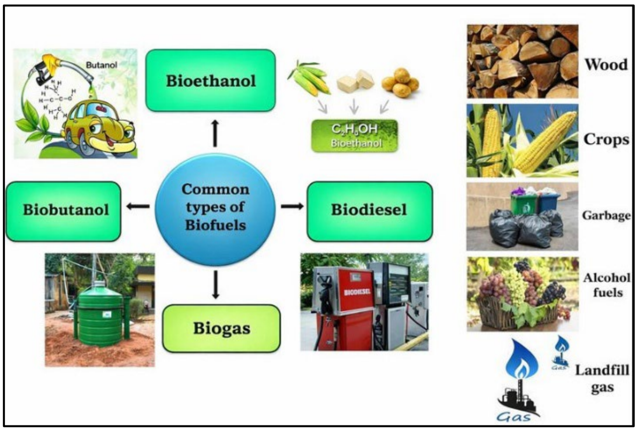

Figure 2. Types of biofuels and the types of biomass to make the biofuels

Despite their promise, biofuels face several sustainability challenges, including land-use change, biodiversity loss, water consumption, high production costs, and limited energy return on investment. Addressing these challenges requires integrated policy frameworks, life cycle assessments, advanced bioprocessing technologies, and prioritisation of waste-based and third-generation biofuels. When strategically implemented, biofuels can play a vital role in global energy transition and climate mitigation efforts. Biofuels constitute an important component of the global renewable energy portfolio, currently contributing approximately 4–5% of total transport fuel demand worldwide, with bioethanol and biodiesel as the dominant commercial fuels [48]. First-generation biofuels derived from sugarcane, corn, and oilseed crops have demonstrated substantial energy substitution potential, particularly in Brazil, the United States, and the European Union; however, their sustainability is strongly contested due to land use change, water and fertilizer intensification, and competition with food crops, giving rise to the long-standing food-versus-fuel debate [44,48]. Life cycle assessment studies reveal that while sugarcane-based ethanol and waste-derived biofuels deliver significant greenhouse gas emission reductions, corn-based ethanol and conventional biodiesel show variable environmental performance depending on cultivation practices and indirect land use effects [49]. In contrast, advanced biofuels, including lignocellulosic ethanol, biogas, and algal biofuels, offer greater long-term sustainability by utilizing non-food biomass, agricultural residues, and waste streams, though their large-scale deployment remains constrained by high production costs, technological complexity, and limited infrastructure [50]. Consequently, the sustainable integration of biofuels into the global energy system requires robust policy frameworks, sustainability certification, feedstock diversification, and alignment with circular bioeconomy principles to balance energy security with environmental and food system resilience.

5. Bioremediation and Phytoremediation

Biological remediation involves the use of microorganisms and/or plants to degrade, detoxify, or immobilise environmental contaminants and includes two major approaches: bioremediation and phytoremediation. Owing to their cost-effectiveness, minimal environmental disturbance, and sustainability, these approaches are increasingly applied for the restoration of polluted soils, sediments, groundwater, and aquatic systems [51]. Recent advancements have demonstrated the feasibility of biological remediation even in complex scenarios such as co-contaminated sites and cold-climate environments [52,53].

Several field-scale applications highlight the practical effectiveness of bioremediation and phytoremediation. In petroleum-contaminated soils, bioaugmentation with hydrocarbon-degrading microbial consortia has resulted in contamination reductions exceeding 60–80% within one year under field conditions [54]. Phytoremediation using hyperaccumulator plants such as *Brassica juncea*, *Pteris vittata*, and *Vetiveria zizanioides* has been successfully employed to remediate soils contaminated with heavy metals including arsenic, cadmium, and lead, achieving significant reductions in bioavailable metal fractions [53].

Constructed wetlands planted with macrophytes such as *Typha latifolia* and *Phragmites australis* have been widely implemented for wastewater treatment and nutrient removal, showing effective reduction of organic matter, nitrogen, and phosphorus while also immobilising trace metals [55]. In cold regions, psychrotolerant bacteria and microalgae have been applied for oil spill remediation, demonstrating substantial biodegradation rates despite low temperatures [52]. Additionally, mycoremediation approaches using ligninolytic fungi such as *Phanerochaete chrysosporium* have shown promise in degrading persistent organic pollutants including polycyclic aromatic hydrocarides (PAHs) and dyes at pilot scale [56]. Tables 1–3 collectively summarise key bioremediation and phytoremediation approaches, highlighting major pollutants, biological agents, enhancement strategies, and reported removal efficiencies under field and applied conditions.

Table 1. Field-scale bioremediation: pollutants, microorganisms, and removal efficiencies

Pollutant type	Target contaminant	Microorganism(s) used	Site/medium	Reported removal efficiency	Reference
Petroleum hydrocarbons	Total petroleum hydrocarbons (TPH)	*Pseudomonas*, *Acinetobacter*, *Rhodococcus* consortium	Oil-contaminated soil	65–85% within 6–12 months	[60]
Polycyclic aromatic hydrocarbons (PAHs)	Phenanthrene, pyrene	*Mycobacterium*, *Sphingomonas* spp.	Soil	60–75%	[61]
Chlorinated solvents	Trichloroethylene (TCE)	*Dehalococcoides mccartyi*	Groundwater	>90% dechlorination	[62]
Heavy metals	Cr(VI)	*Bacillus subtilis*, *Shewanella* spp.	Industrial effluent	70–95% reduction	[63]
Nutrients	Nitrate, phosphate	Mixed bacterial consortia	Wastewater	60–80% nutrient removal	[55]

Table 2. Phytoremediation: plants, contaminants, and remediation performance

Plant species	Contaminant	Mechanism	Medium	Efficiency / outcome	Reference
Brassica juncea	Pb, Cd	Phytoextraction	Soil	50–70% reduction in bioavailable metals	[53]
Pteris vittata	Arsenic	Hyperaccumulation	Soil	>80% arsenic uptake	[51]
Vetiveria zizanioides	Zn, Pb, Cu	Phytostabilisation	Soil	Significant reduction in metal mobility	[59]
Typha latifolia	Nutrients, metals	Rhizofiltration	Constructed wetlands	60–90% nutrient removal	[55]
Helianthus annuus	Cd, Pb	Phytoextraction	Soil	40–60% uptake	[64]

Table 3. Enhanced bioremediation approaches and performance

Enhancement strategy	Amendment / approach	Target pollutant	Improvement over conventional method	Reference
Microbial immobilisation	Alginate beads, biochar	Hydrocarbons	20–40% higher degradation rate	[57]
Microbial consortia	Bacteria–algae systems	Mixed contaminants	Improved resilience and efficiency	[65]
Nanomaterials-assisted	Nano-Fe_3O_4, biochar	Heavy metals, PAHs	Enhanced bioavailability & removal	[63]
Organic amendments	Poultry manure, compost	Petroleum hydrocarbons	Faster degradation kinetics	[46]
Mycoremediation	*Phanerochaete chrysosporium*	Dyes, PAHs	>70% pollutant breakdown	[61]

Despite its advantages, biological remediation faces several limitations. The process is inherently slow and often constrained by low pollutant bioavailability, nutrient limitations, environmental stress factors, and toxicity thresholds that inhibit microbial or plant growth [57]. Phytoremediation is limited by plant biomass, root depth, and growing seasons, and may be ineffective for deeply buried contaminants. Furthermore, the accumulation of heavy metals in plant tissues raises concerns regarding biomass disposal and secondary pollution risks [51].

Bioremediation performance can also be inconsistent due to site heterogeneity, fluctuating environmental conditions, and competition between introduced and native microorganisms. The use of amendments such as nanomaterials or chemical agents, while enhancing contaminant availability, may introduce ecotoxicological risks if not carefully managed [58].

Future research should focus on integrating omics-based approaches (metagenomics, proteomics, and metabolomics) to better understand microbial community dynamics and functional pathways during remediation processes. The development of genetically engineered microorganisms and plants with enhanced degradation or accumulation capacities represents a promising but ethically and regulatory challenging avenue [59]. Greater emphasis is also needed on field-scale validation, long-term monitoring, and life cycle assessment (LCA) to evaluate the sustainability and environmental trade-offs of biological remediation technologies.

Hybrid approaches that combine bioremediation with physicochemical methods, as well as the strategic use of microbial consortia, biochar, and green nanomaterials, are expected to enhance remediation efficiency. Strengthening regulatory frameworks, stakeholder engagement, and risk assessment protocols will be essential for translating laboratory success into reliable field-scale solutions.

6. Biopesticides and Biofertilizers

Synthetic (chemical) pesticides have been used since ancient times to manage agricultural pests and increase crop yields [66]. The chemicals and carriers used to make synthetic pesticides, like polymers, are unique to particular pests [67]. According to their classification, they include those used to control weeds (herbicides), algae (algicides), fungi (fungicides), mites or ticks (miticides/acaricides), bacteria (bactericides), rodents (rodenticides), insects (insecticides),termites (termiticides), molluscs (molluscicides), and nematodes (nematicides) [68]. Organochlorines, diazinon, diamide, dichlorvos, chlorpyrifos, and other active components can be used as another basis for classifying pesticides. Synthetic pesticides have some detrimental consequences on soil biodiversity, animals, aquatic life, and humans, despite their beneficial effects on agricultural output and productivity [69]. According to Pertile et al. [70], synthetic pesticides typically cause the soil to become brittle, decrease soil respiration, and decrease the activity of some soil macroorganisms, like earthworms. Additionally, they diminish vitality, disease resistance, the traits of the progeny, and the success of animal mating [71]. By reducing their biological services in the synthesis of specific features that promote plant growth, including siderophores, nitrogen, indole-3-acetic, etc., they have a detrimental effect on soil microorganisms [72]. A decrease in the photosynthetic capacity and seed production of certain non-targeted plants occurs when synthetic pesticides enter the environment through a variety of channels, including vapour movements, careless disposal, droplet drift, erosion, and leaching [73].

Biopesticides are inexpensive, environmentally benign, selective in their mechanism of action, long-lasting, residue-free, and not linked to greenhouse gas emissions [74]. These biopesticides can be classified as microbial pesticides (made from microorganisms) [75], phytopesticides (made from plants) [76], or nanobiopesticides (made from biological agents like nanoparticles) [77]. In contrast to synthetic pesticides, microbial pesticides are environmentally sustainable, have no lasting effects, are easily available, and are particular in their activity [75]. In addition to having a wide range of phytochemical substances that enable them to exhibit different mechanisms of action, phytopesticides pose fewer health hazards to humans and are not linked to the generation of greenhouse gases [76]. Compared to synthetic pesticides, nanobiopesticides have superior biocompatibility, biodegradability, targeted or controlled release, and greater pesticidal activity [77]. The blockage and destruction of diseases' and pests' plasma membranes and protein translation are two of the various ways that biopesticides work. In contrast to synthetic pesticides, biopesticides are extremely precise in their target, have a brief shelf life, are less persistent in the surrounding environment, and are made from sustainable raw materials, despite a few disadvantages that have decreased their acceptability and commercial use [72]. Some of the above-mentioned benefits of biopesticides may potentially be drawbacks. For instance, if controlling numerous pests at once is the goal, their pest-specificity may work against them. Additionally, because of their short shelf life, they decompose quickly and are less persistent in the environment, which is a drawback if the objective is to eradicate all current pests and stop the growth of new ones that will emerge after the biopesticides are applied (Fig. 3).

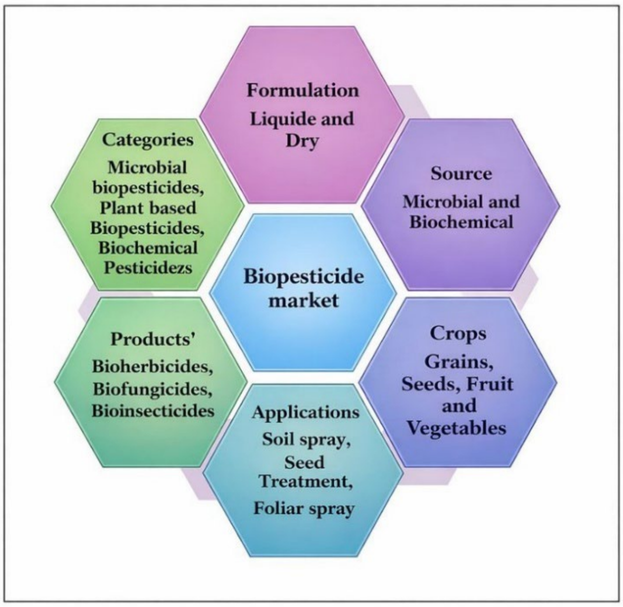

Fig. 3. Different types of Biopesticides available in the market

In order to supply the need for food, chemical fertilisers help plants to grow quickly and efficiently. The negative effects of using more chemical or synthetic fertilisers include pollution of the environment, long-term changes in the physiochemical composition and ecology of the soil, a decline in agricultural production, and other health risks. Abiotic stress on crops is exacerbated by climate variables, which lowers agricultural productivity. Soil salinity, drought, wind, incorrect temperature, waterlogging, heavy metals, and numerous weeds and phytopathogens, such as bacteria, viruses, fungus, and nematodes, are examples of abiotic and biotic stressors that harm plants and lower crop quality and productivity. All of these facts have led to a shift in the use of biofertilizers, which offer nutrition through natural processes such as nitrogen fixation, siderophore, hormone production, zinc, potassium, and phosphorus solubilisation, as well as protecting plants from various plant diseases and stressors. In addition to being environmentally friendly and conveniently priced, they supply enough nutrients for the establishment of healthy crops that will meet the demands of the world's growing population.

While the word "biofertilizer" refers to the employment of microbes to meet nutritional needs, "microbial bioinoculant" is used in other nations [78]. The bioavailability and bioaccessibility of nutrients taken up in plants can be enhanced by biofertilizers, which are bio-based organic fertilisers derived from either plant or animal sources or from dormant or alive microbial cells [79]. According to Bhardwaj et al. [80], a key component of biofertilizers is live microbial mass. "The preparations containing live microbes that help to improve soil fertility by fixing atmospheric nitrogen, solubilising phosphorus, or decomposing organic wastes, or by increasing plant growth via the generation of growth hormones through their biological activities" is the correct definition of biofertilizers [81]. After being packed onto appropriate carriers including rice bran, clay minerals, peat, wheat bran, lignite, humus, and wood charcoal, biofertilizers are often applied in solid or dry forms. Carriers make it easier to handle microbial inoculants and extend their shelf life [82]. According to Chaudhary et al. [83,84], biofertilizers have several advantages, such as reduced costs, increased nutrient availability, improved soil fertility, protection of plants from soil-borne pathogens, environmentally friendly farming, improved biotic and abiotic stress tolerance, increased phytohormone production, improved soil health, reduced environmental pollution, and significantly improved soil fertility with continued use.

Global biofertilizer is marketed under two main categories, such as microorganism-based biofertilizer and organic residue-based biofertilizer, depending on the source and raw material. The most common organic-based biofertilizers include farmyard manure, green manure, crop residues, and treated sewage sludge. Conversely, helpful microorganisms such as bacteria, fungus, and algae are present in microorganism-based biofertilizers. These biofertilizers mediate plant growth performance either directly or indirectly. Nitrogen fixation, phosphate solubilisation, micronutrient solubilisation, and phytohormone synthesis are examples of direct mechanisms that directly affect plants [84]. By releasing lytic enzymes, antibiotics, siderophores, and cyanide generation, the indirect mechanism typically shields the plant from the harmful effects of the pathogens [85] (Figure 4).

Despite the well-documented environmental and agronomic benefits of biopesticides and biofertilizers, their large-scale adoption remains limited due to several technical, regulatory, and market-related constraints. One of the primary adoption barriers is inconsistent field performance, which is strongly influenced by soil type, climatic conditions, microbial survival, and interactions with native microbiota [35; 86]. Farmers often perceive biological inputs as slower-acting and less reliable than synthetic agrochemicals, particularly under high pest pressure or nutrient-deficient conditions.

Another major limitation is short shelf life and storage instability, especially for microbial formulations, which increases transportation and handling costs and reduces farmer confidence [87]. Additionally, lack of awareness, technical knowledge, and training among farmers, particularly in developing countries, hampers effective application and acceptance [88].

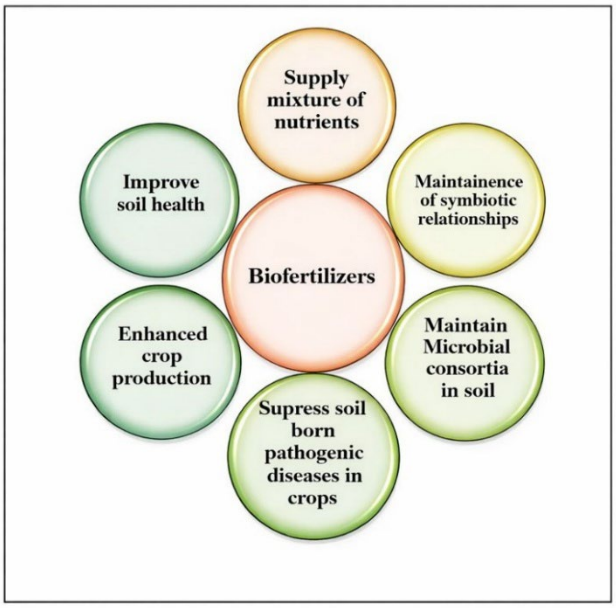

Fig. 4. Role of Biofertilizers in sustainable agriculture

From a regulatory perspective, stringent, fragmented, and time-consuming approval processes significantly delay product commercialization. Regulatory frameworks for biopesticides and biofertilizers are often adapted from chemical pesticide regulations, which are not well-suited to biological products and increase compliance costs [89; 90]. Variability in regulations across countries further restricts international market expansion and technology transfer.

Commercial viability is also affected by high production costs, scale-up challenges, and limited private-sector investment. Maintaining microbial viability during mass production, formulation, and storage requires specialized infrastructure and quality control systems, increasing production expenses [91; 92]. Moreover, weak policy incentives and limited integration into mainstream agricultural subsidy schemes reduce market competitiveness compared to synthetic inputs.

Nevertheless, recent advances in nanocarriers, encapsulation technologies, consortium-based formulations, and precision agriculture integration are improving efficacy, stability, and cost-effectiveness, enhancing future commercial prospects [93;94]. Stronger policy support, harmonized regulations, farmer training programs, and public–private partnerships are essential to accelerate adoption and mainstream biological alternatives in sustainable agriculture. The tables 4 -6 summarise recent large-scale field applications of biopesticides and biofertilizers, highlighting crop systems, biological inputs, scale of implementation, and comparative performance in improving pest control, nutrient use efficiency, and crop productivity.

Table 4. Large-Scale Applications of Biopesticides

Case Study / Location	Biopesticide Type	Target Crop / Pest	Scale	Key Outcomes / Metrics	Reference
India (Punjab)	*Bacillus thuringiensis* (microbial)	Helicoverpa armigera in cotton	~10,000 ha	65–75% pest suppression, 20–30% yield increase vs control	[95]
Brazil (Cerrado)	Neem oil extract (phytopesticide)	Spodoptera frugiperda in maize	~8,500 ha	55–70% reduction in larval incidence	[96]
Spain (Andalusia)	*Beauveria bassiana* formulation	Tuta absoluta in tomatoes	~4,200 ha	60–80% decrease in pest population	[97]
Kenya (Rift Valley)	Nano-chitosan biopesticide	Fall armyworm in maize	~7,000 ha	50–65% pest control; reduced mycotoxin incidence	[98]
China (Shandong)	*Trichoderma harzianum*	Multiple fungal pathogens in wheat	~9,000 ha	30–45% disease suppression, improved grain quality	[99]

Table 5. Large-Scale Applications of Biofertilizers

Case Study / Location	Biofertilizer Type	Crop	Scale	Key Outcomes / Metrics	Reference
India (Madhya Pradesh)	Rhizobium + PSB consortium	Soybean	~12,500 ha	15–25% yield increase, 20–30 kg N/ha fixed	[56]
Nigeria (Kaduna)	*Azospirillum brasilense*	Maize	~5,800 ha	12–22% yield increase, improved drought tolerance	[100]
USA (Midwest)	Mycorrhizal biofertilizer	Corn	~18,000 ha	8–15% increased nutrient uptake	[101]
Brazil (São Paulo)	*Bacillus subtilis* + PSB	Sugarcane	~10,200 ha	18–27% increase in sugar yields	[102]
Vietnam (Mekong Delta)	Azolla + N-fixing cyanobacteria	Rice paddies	~7,500 ha	40–55 kg N/ha fixed; 10–18% yield gain	[103]

Table 6. Comparative Performance vs Conventional Inputs

Application	Biological Input	Conventional Input	Comparative Performance	Reference
Cotton pest control (India)	*Bacillus thuringiensis*	Synthetic insecticide	Similar pest suppression; lower non-target effects	[95]
Maize nutrient management (Nigeria)	*Azospirillum brasilense*	Chemical N fertilizer	60–75% of fertilizer N used; reduced leaching	[100]
Tomato fungal disease (Spain)	*Beauveria bassiana*	Synthetic fungicides	Comparable suppression; improved pollinator safety	[97]
Wheat soil health (China)	*Trichoderma harzianum*	Fungicide + fertilizer	15% higher SOC; lower inputs	[99]
Rice paddies (Vietnam)	Azolla + cyanobacteria	Full chemical N	~40% cost saving; 10–18% yield gain	[103]

7. Challenges and Future Perspectives

Despite significant advances, the widespread adoption of sustainable biotechnological approaches—such as bioplastics, bioenzymes, biofuels, bioremediation, biopesticides, and biofertilizers—continues to face key challenges related to scalability, cost-effectiveness, regulatory complexity, and inconsistent field performance. Many bio-based solutions exhibit variability under different environmental conditions, limited shelf life, and difficulties in large-scale production and storage, which restrict their commercial competitiveness against conventional chemical alternatives [86; 90]. In addition, fragmented regulatory frameworks, lack of standardized testing protocols, and low farmer and industry awareness further slow market penetration, particularly in developing regions [88; 89]. From a sustainability perspective, unresolved concerns remain regarding life-cycle impacts, land-use change, and the food–fuel–materials trade-offs associated with biomass utilization [93; 94]. Future progress will depend on advances in systems biology, synthetic biology, nanobiotechnology, and microbial consortia design to improve efficiency, robustness, and environmental compatibility. Equally important are supportive policies, harmonized regulations, public–private partnerships, and capacity-building initiatives to enable large-scale deployment. Integrating these innovations within circular bioeconomy models offers strong potential to align biotechnology-driven solutions with global sustainability goals, particularly SDGs 12, 13, and 14.

8. Conclusion

Sustainable biotechnology offers a versatile toolkit to address global environmental and agricultural challenges, including pollution remediation, waste valorization, renewable energy production, and eco-friendly crop management. Across bioplastics, bioenzymes, biofuels, bioremediation, biopesticides, and biofertilizers, the chapter highlights the potential for these biological solutions to reduce reliance on chemical inputs, lower greenhouse gas emissions, and enhance resource efficiency. While significant advances have been made, the widespread adoption of these technologies is constrained by scalability issues, regulatory complexities, inconsistent field performance, and economic factors. Future progress will depend on innovations in microbial consortia, synthetic biology, nanobiotechnology, and process optimization, alongside supportive policies, harmonized regulations, and capacity-building initiatives.

Key Takeaways:

1. Environmental Sustainability: Biological alternatives reduce chemical pollution, improve soil and water health, and contribute to climate mitigation.
2. Agronomic Benefits: Biofertilizers and biopesticides enhance crop growth, nutrient use efficiency, and pest/disease management with minimal environmental impact.
3. Waste Valorization: Bioenzymes, bioplastics, and biofuels provide value-added solutions from agricultural and household waste streams.
4. Technological Challenges: Large-scale application requires addressing short shelf life, variable field performance, production costs, and regulatory hurdles.
5. Future Opportunities: Integrating biotechnology with circular economy principles, advanced formulation technologies, and precision agriculture can improve efficiency and adoption.
6. Alignment with SDGs: These approaches contribute directly to SDG 2 (Zero Hunger), SDG 7 (Affordable and Clean Energy), SDG 12 (Responsible Consumption and Production), SDG 13 (Climate Action), and SDG 14 (Life Below Water).

Overall, sustainable biotechnology represents a critical pathway to reconcile human development with environmental stewardship, offering scalable solutions to meet the demands of a growing population while preserving planetary health.

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