

GREEN TECHNOLOGIES FOR BIODIVERSITY CONSERVATION AND
ENVIRONMENTAL SUSTAINABILITY: A REVIEW

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Abstract

The accelerating decline of global biodiversity, driven by habitat destruction, climate change, pollution, overexploitation, and unsustainable agricultural practices, poses an existential threat to ecosystem stability and human well-being. In response, green technologies have emerged as transformative tools for reconciling economic development with environmental sustainability. This review provides a comprehensive synthesis of green technological innovations applied to biodiversity conservation and environmental sustainability, spanning renewable energy systems, environmental biotechnology, precision agriculture, smart monitoring technologies, and digital conservation tools. The analysis examines the conceptual foundations of green technology, evaluates its applications across terrestrial, freshwater, and marine ecosystems, and critically assesses the associated trade-offs and ecological risks. Key findings reveal that while technologies such as remote sensing, environmental DNA analysis, AI-driven species identification, and bioremediation offer unprecedented opportunities for monitoring and restoring biodiversity, their deployment must be carefully managed to avoid unintended consequences, including habitat fragmentation from renewable energy infrastructure and e-waste generation. The review highlights the importance of strategic planning, such as the mitigation hierarchy for renewable energy siting, and the integration of nature-based solutions with technological interventions. Challenges including high costs, technical capacity gaps, data interoperability

issues, and inequitable access disproportionately affect developing nations with the greatest biodiversity richness. Policy frameworks, including the Kunming-Montreal Global Biodiversity Framework, provide crucial enabling conditions for scaling green technologies, yet implementation remains uneven. The review concludes that realizing the full potential of green technologies requires interdisciplinary collaboration, robust governance structures, increased investment, and a commitment to biodiversity-positive technological development that aligns with planetary sustainability goals.

1. INTRODUCTION

The contemporary era is witnessing an unprecedented acceleration in biodiversity loss and environmental degradation, phenomena that collectively represent one of the most profound challenges to planetary health and human wellbeing. Global biodiversity is declining at rates unparalleled in human history, with species extinction rates now estimated to be tens to thousands of times higher than the natural background rate. This biological impoverishment is accompanied by widespread environmental degradation encompassing soil depletion, freshwater scarcity, atmospheric pollution, and the disruption of biogeochemical cycles. The interconnected nature of these crises demands integrated responses that address both the symptoms and underlying drivers of ecological decline[1]. The Kunming-Montreal Global Biodiversity Framework, adopted under the Convention on Biological Diversity, establishes ambitious targets for halting and reversing biodiversity loss by 2030. These targets recognize that biodiversity conservation cannot be pursued in isolation from broader sustainability goals, including climate change mitigation and sustainable development. Similarly, the Paris Agreement on climate change acknowledges the inseparable links between climate stabilization and ecosystem integrity. These international frameworks signal a growing consensus that transformative approaches are required to address the intertwined challenges of biodiversity loss, climate change, and environmental degradation. Policymakers now recognize the importance of joint action on climate change and biodiversity loss, as each, without the other, is insufficient[2]. The conversion of natural ecosystems for agriculture, urban development, and

infrastructure constitutes the primary driver of biodiversity loss globally. Habitat fragmentation isolates populations, reduces genetic diversity, and disrupts ecological processes essential for species persistence. Activities and infrastructure related to the renewable energy transition can affect biodiversity both positively and negatively, with renewable energy infrastructure and the mining of materials needed for these technologies associated with large-scale land conversion[3]. Rising global temperatures, shifting precipitation patterns, and increasing frequency of extreme weather events are altering species distributions, disrupting phenological synchrony, and pushing ecosystems toward critical tipping points. Climate change interacts synergistically with other stressors, amplifying their impacts on vulnerable species and ecosystems. Climate change threatens biodiversity, making a rapid energy transition essential for human and ecological well-being[4]. Chemical contamination of air, water, and soil affects biodiversity at all levels of biological organization. Persistent organic pollutants, heavy metals, agricultural runoff, and plastic pollution exert direct toxic effects on organisms while also disrupting reproductive success, immune function, and ecosystem functioning. The increasing burden of municipal solid waste, petroleum hydrocarbons, industrial wastewater, saline soils, marine pollution, electronic wastes, and plastic contaminants is among the foremost global environmental issues that need sustainable remediation practices[5]. Unsustainable harvesting of wildlife, fisheries, and timber resources continues to drive species declines despite regulatory frameworks. Illegal wildlife trade represents a particularly acute threat to many endangered species. The introduction of non-native species disrupts ecological

communities through predation, competition, disease transmission, and hybridization. Invasive species are a leading cause of extinction on islands and increasingly threaten mainland ecosystems[6]. Modern agricultural practices, characterized by monocultures, intensive chemical inputs, and landscape homogenization, have dramatically reduced farmland biodiversity. Intense herbicide selection pressure has resulted in the evolution and spread of herbicide-resistant weeds, selecting for even fewer dominant weed species and further reducing field-scale weed species diversity. Industrial expansion continues to encroach upon remaining natural habitats[7]. Environmental sustainability encompasses the maintenance of ecosystem functions and services essential for human wellbeing while ensuring that natural resource use does not exceed regenerative capacities. The concept is anchored in the recognition that economic development and human welfare depend ultimately upon healthy, functioning ecosystems. Sustainability thinking emphasizes intergenerational equity, precautionary approaches to environmental management, and the integration of ecological considerations into all aspects of decision-making[8]. Green technologies have evolved from niche innovations to mainstream solutions across multiple sectors. The concept encompasses technologies designed to reduce environmental impacts, enhance resource efficiency, and restore degraded ecosystems. Early green technologies focused primarily on pollution control and waste treatment, but contemporary approaches embrace system-level transformations encompassing renewable energy, sustainable agriculture, ecosystem monitoring, and circular economy principles. The evolution of green technologies has been driven by growing environmental awareness, policy incentives, technological advances, and increasing recognition of the economic opportunities associated with sustainability transitions[9].

Technologies like satellite monitoring, artificial intelligence, the Internet of Things, and blockchain have emerged as powerful tools supporting real-time forest trackers, preventing illicit logging activities, and enabling better

utilization of forest resources. These technologies facilitate decision-making based on data and new environment that allows for rapid response to forest fires and pests. In addition, green technologies can improve reforestation prospects through precision planting and data mining[10]. Technological innovation offers unprecedented opportunities for biodiversity conservation across spatial and temporal scales. Advanced monitoring technologies enable the detection and tracking of species and ecosystems with increasing precision and efficiency. Conservation technologies support protected area management, combat illegal wildlife trade, and inform evidence-based conservation planning. However, technology is not a panacea; its application must be guided by ecological principles and implemented within broader conservation strategies that address the fundamental drivers of biodiversity loss[11]. Remote sensing-based habitat mapping and monitoring can serve as a backbone for biodiversity policy and ecosystem stewardship, providing timely and transparent evidence to guide restoration, inform nature-based solutions, and track progress towards climate and biodiversity goals at multiple scales. Cloud-native, open workflows linked with FAIR data, semantic crosswalks, and transparent uncertainty can deliver the consistent, auditable indicators required for global initiatives under the SDGs and the Convention on Biological Diversity[12].

The complexity of environmental challenges demands integrated approaches that combine multiple technologies and strategies. No single technology can address the full spectrum of conservation and sustainability challenges. Integrated approaches leverage synergies among technologies while mitigating trade-offs. The convergence of biotechnologies from different fields offers synergistic benefits, leading to innovative solutions that address multiple environmental issues simultaneously. Integrating biotechnologies such as synthetic biology, genomics, and bioremediation can result in holistic solutions[13]. For example, bioreactors utilizing engineered microorganisms for carbon sequestration can also purify water and generate bioenergy, reducing atmospheric CO₂ while

improving water quality and generating renewable energy. Furthermore, platforms integrating data from biosensors, genomic databases, and remote sensing technologies can provide comprehensive environmental monitoring and management solutions, enabling real-time data integration and analysis that supports more informed decision-making and adaptive management strategies[14]. This review provides a comprehensive examination of green technologies for biodiversity conservation and environmental sustainability. The objectives are to: (1) synthesize the current state of knowledge on green technologies across multiple sectors; (2) evaluate the applications, benefits, and limitations of these technologies; (3) identify challenges and barriers to implementation; and (4) outline future directions for technology development and deployment. The review is novel in its integrative scope, covering technologies from monitoring and assessment through to restoration and sustainable resource management, while also addressing the critical intersections between biodiversity conservation and other sustainability goals.

2. Conceptual Framework of Green Technologies

2.1. Definition and Principles of Green Technology

Green technologies encompass products, processes, and systems that reduce environmental impacts, conserve natural resources, and support ecological restoration. The defining principles of green technology include: (1) pollution prevention rather than end-of-pipe control; (2) resource efficiency and waste minimization; (3) use of renewable rather than finite resources; (4) design for environmental compatibility and circularity; and (5) integration with ecological systems. Green technologies may be distinguished by their emphasis on systemic sustainability rather than merely reducing specific environmental impacts[15].

2.2. Green Technology versus Conventional Technologies

The distinction between green and conventional technologies lies in their environmental performance across full life cycles. Green

technologies are characterized by lower resource consumption, reduced emissions, and enhanced ecological compatibility. However, the boundaries are not always clear-cut; conventional technologies may incorporate green features, and green technologies can have unintended environmental consequences. Life-cycle assessment provides a systematic framework for comparing environmental performance and identifying trade-offs[16].

2.3. Relationship between Green Technology, Conservation, and Sustainability

Green technologies serve as enabling tools for conservation and sustainability, yet they are not sufficient in themselves. Conservation outcomes depend on the appropriate application of technologies within enabling policy and institutional frameworks. Sustainability requires that technology deployment respects ecological limits and supports social equity. The relationships among green technology, conservation, and sustainability are dynamic; technologies may create new opportunities for conservation while also posing novel risks that require careful management[11].

2.4. Major Categories of Green Technologies

Solar, wind, hydropower, geothermal, bioenergy, and green hydrogen provide alternatives to fossil fuels while reducing greenhouse gas emissions and air pollution. Biomass plays a pivotal role in the transition from a fossil fuel-dependent economy to one that is more sustainable and environmentally friendly, with applications including bio-based products, biogas technology, biomass electricity generation, biodiesel technology, feedstock processing, and fuel ethanol technology. Bioremediation, phytoremediation, microbial remediation, and related approaches use biological systems to clean contaminated environments and restore ecosystem functions[17]. Various in situ and ex situ remediation techniques like bioaugmentation, biostimulation, biosparging, land farming, composting, bioreactor techniques, activated sludge process, algal remediation, and fungal-based remediation techniques are highly efficient for the degradation of hydrocarbons, dyes,

pharmaceutical compounds, heavy metals, volatile organic compounds, and new-age plastic pollutants. Sensor-based, data-driven farming approaches optimize inputs, reduce environmental impacts, and maintain productivity. Precision agriculture can foster cropland weed diversity and protect endangered species by allowing individual plant-level management and selective elimination of undesirable species[18]. Remote sensing, environmental DNA, automated acoustic monitoring, camera traps, and artificial intelligence enable comprehensive biodiversity assessment. Close-range remote sensing of forest structure supports biodiversity assessments through technologies like airborne laser scanning and terrestrial laser scanning. Recycling, composting, anaerobic digestion, and waste-to-energy systems reduce landfill pressure and recover resources. Advanced treatment processes, constructed wetlands, and membrane technologies protect water quality and aquatic ecosystems. Sustainable building materials, green roofs, ecological corridors, and nature-based

solutions integrate environmental considerations into built environments. Carbon capture, utilization, and storage, direct air capture, biochar, and nature-based sequestration address climate change[19].

2.5. Technology–Environment Interactions and Sustainability Trade-offs

Green technologies interact with the environment through complex pathways that may include both benefits and costs. Renewable energy infrastructure requires land conversion and resource extraction with potential biodiversity impacts. Monitoring technologies may disturb sensitive species. The concept of sustainability trade-offs acknowledges that technological solutions may create new environmental challenges while addressing others. Strategic thinking is required to ensure that the energy transition and other technology deployments benefit biodiversity rather than inadvertently harming it[20].

Table 1. Major Green Technologies and Their Applications in Biodiversity Conservation and Environmental Sustainability [21], [22]

Technology Category	Key Technologies	Primary Applications	Biodiversity Relevance
Monitoring & Assessment	Remote sensing, GIS, drones, eDNA, acoustic monitoring, camera traps, AI	Species detection, habitat mapping, population monitoring, threat detection	Enables comprehensive biodiversity assessment across scales
Renewable Energy	Solar, wind, hydropower, geothermal, bioenergy, green hydrogen	Clean energy production, climate change mitigation	Reduces fossil fuel emissions but requires careful siting to avoid habitat impacts
Environmental Biotechnology	Bioremediation, phytoremediation, microbial remediation, synthetic biology	Pollution remediation, ecosystem restoration, waste treatment	Restores contaminated habitats, supports species recovery
Precision Agriculture	Sensor-based farming, smart irrigation, agricultural drones, biofertilizers	Sustainable crop production, input reduction	Supports farmland biodiversity, reduces chemical inputs
Water Technologies	Advanced treatment, membrane technologies, constructed wetlands	Water purification, aquatic ecosystem protection	Maintains water quality for freshwater biodiversity

Waste Management	Recycling, anaerobic digestion, composting, waste-to-energy	Waste reduction, resource recovery	Reduces habitat degradation from waste disposal
Green Infrastructure	Green buildings, green roofs, urban forests, ecological corridors	Urban sustainability, habitat connectivity	Supports urban biodiversity, reduces fragmentation
Carbon Removal	CCUS, direct air capture, biochar, nature-based sequestration	Climate change mitigation	Addresses climate-driven biodiversity loss

3. Green Technologies for Biodiversity Monitoring and Assessment

3.1. Remote Sensing and Satellite-Based Monitoring

Satellite-based remote sensing provides systematic, repeatable observations of Earth's surface at multiple spatial and temporal scales. Earth observation satellites enable the monitoring of habitat extent and condition, land-use change, deforestation, and ecosystem dynamics across entire continents. Optical, radar, and LiDAR sensors capture different aspects of ecosystem structure and functioning. Advances in satellite technology have increased spatial resolution, spectral coverage, and temporal frequency while reducing costs[23].

Remote sensing-based habitat mapping and monitoring can serve as a backbone for biodiversity policy and ecosystem stewardship, providing timely and transparent evidence to guide restoration, inform nature-based solutions, and track progress towards climate and biodiversity goals at multiple scales. Cloud-native, open workflows linked with FAIR data, semantic crosswalks and transparent uncertainty can deliver the consistent, auditable indicators required for global initiatives under the SDGs and the Convention of Biological Diversity[12].

3.2. Geographic Information Systems (GIS)

Geographic Information Systems integrate spatial data with analytical capabilities to support conservation decision-making. GIS enables the mapping of species distributions, habitat suitability, land-use patterns, and conservation priorities. Spatial analyses inform the design of protected area networks, ecological corridors, and

habitat restoration projects. GIS-based approaches incorporate multiple data layers to assess cumulative impacts, identify conservation gaps, and evaluate alternative scenarios. Conservation GIS has evolved from simple mapping to sophisticated spatial modeling that integrates ecological, social, and economic dimensions[24].

3.3. Drones and Unmanned Aerial Vehicles

Unmanned aerial vehicles (UAVs) or drones provide flexible, cost-effective platforms for biodiversity monitoring at fine spatial scales. Drones equipped with optical, multispectral, thermal, or LiDAR sensors capture high-resolution data on vegetation structure, wildlife populations, and habitat condition. Applications include wildlife censuses, nest surveys, habitat mapping, and the detection of illegal activities. Drone-based monitoring can access remote or hazardous areas and provide repeated observations with minimal disturbance. The integration of artificial intelligence with drone imagery enables automated species detection and classification. However, drone operations must consider potential disturbance to wildlife and comply with aviation regulations[25].

3.4. Environmental DNA (eDNA) and Metabarcoding

Environmental DNA analysis detects the presence of species from DNA shed into the environment through skin, feces, mucus, or gametes. Water, soil, or sediment samples are collected and analyzed for DNA fragments, which are amplified and sequenced to identify species. Metabarcoding extends this approach to characterize entire communities from environmental samples. eDNA

has revolutionized biodiversity assessment, enabling detection of rare, cryptic, or difficult-to-observe species. Applications include aquatic biodiversity surveys, invasive species detection, and monitoring of threatened species. eDNA-based surveillance provides comprehensive, non-invasive biodiversity data that complement traditional survey methods[26].

3.5. Automated Acoustic Monitoring

Acoustic monitoring records soundscapes to document species presence, activity patterns, and community composition. Automated recording units capture vocalizations of birds, amphibians, insects, and mammals. Advances in machine learning enable automated species identification from acoustic data, dramatically reducing analysis time. Acoustic monitoring provides continuous, non-invasive data at large spatial and temporal scales. Applications include biodiversity assessments, population monitoring, and the detection of phenological shifts. The approach is particularly valuable for assessing vocalizing species in forested habitats where visual surveys are challenging[27].

3.6. Camera Traps and Automated Image Recognition

Camera traps provide non-invasive monitoring of wildlife through motion-triggered photography. Applications include population estimation, occupancy modeling, and behavioral studies. Camera trap data support the conservation of rare and elusive species, inform protected area management, and detect illegal activities. The growing volume of camera trap data has driven the development of automated image recognition tools based on machine learning. While challenges remain in standardization and data management, camera trapping has become a cornerstone of wildlife monitoring globally[28].

3.7. Artificial Intelligence and Machine Learning for Species Identification

Machine learning algorithms have transformed biodiversity data analysis, enabling automated species identification from images, acoustic recordings, and genetic sequences. Deep learning

models achieve high accuracy for many taxonomic groups, matching or exceeding human expert performance. AI-based identification enables large-scale analysis of biodiversity data that would be infeasible with manual approaches. Applications extend to species distribution modeling, population estimation, and the detection of rare species. Machine learning also supports the analysis of social media and citizen science data for biodiversity monitoring. Technologies like satellite monitoring, AI, IoT, and blockchain provide tools to support real-time forest trackers, preventing illicit logging and enabling better utilization of forest resources[11].

3.8. Internet of Things (IoT)-Based Ecological Monitoring

The Internet of Things connects sensors, cameras, acoustic recorders, and other monitoring devices into integrated networks for real-time environmental data collection. IoT-based systems enable continuous monitoring of ecological parameters, species presence, and environmental conditions. Wireless sensor networks reduce the need for human intervention in remote areas. Real-time data transmission supports early warning systems for wildfires, poaching, and other threats. The scaling of IoT-based monitoring is limited by data management, power requirements, and connectivity in remote areas[29].

3.9. Big Data and Predictive Biodiversity Modelling

The accumulation of biodiversity data from multiple sources enables predictive modeling of species distributions, population dynamics, and ecological responses to environmental change. Machine learning and statistical models relate species occurrence data to environmental covariates to predict habitat suitability and future distributions. Predictive models inform conservation planning, climate change vulnerability assessments, and the evaluation of management scenarios. The integration of ecological, climatic, and socioeconomic data enables comprehensive assessments of biodiversity risks and opportunities[30].

Table 2. Digital Technologies Used for Biodiversity Monitoring [31], [32], [33], [34]

Technology	Application	Spatial Scale	Temporal Resolution	Key Advantages	Limitations
Satellite Remote Sensing	Habitat mapping, deforestation detection, land-use change	Global to regional	Days to weeks	Synoptic coverage, repeatability, historical archive	Coarse resolution for some sensors, cloud cover
GIS	Spatial analysis, conservation planning	Regional to local	Variable	Integration of multiple data layers, scenario modeling	Data quality dependent, expertise required
Drones/UAVs	Wildlife censuses, habitat mapping, threat detection	Local	Hours to days	High resolution, flexible deployment, low cost	Limited coverage, regulatory constraints, disturbance risk
eDNA/Metabarcoding	Species detection, community characterization	Local	Days to weeks	Non-invasive, detects rare/cryptic species, comprehensive	Primer bias, degradation concerns, reference database gaps
Acoustic Monitoring	Species presence, community composition, phenology	Local to landscape	Continuous	Non-invasive, automated analysis, cost-effective	Species with limited vocalizations, background noise
Camera Traps	Population estimation, occupancy, behavior	Local	Continuous	Non-invasive, visual confirmation, behavioral data	Detection probability issues, data management burden
AI/Machine Learning	Species identification, distribution modeling	Variable	Variable	Automated analysis, pattern recognition, scalability	Training data requirements, algorithmic bias
IoT Networks	Real-time environmental monitoring	Local to regional	Continuous	Real-time data, early warning, integration	Power requirements, connectivity, data management
Big Data/Predictive Modeling	Risk assessment, conservation prioritization	Variable	Variable	Integration of diverse data, scenario testing	Data gaps, uncertainty, model validation

4. Renewable Energy and Biodiversity Conservation

The renewable energy transition is essential for addressing climate change, yet its biodiversity implications are complex and context-dependent. Biodiversity outcomes vary markedly with where, how, and which renewable technologies are deployed. While some technologies, such as hydropower, have received substantial scientific attention, others remain comparatively understudied. Consolidating the available evidence is therefore critical to support an effective science-policy dialogue[35].

4.1. Solar Energy

Solar energy technologies convert sunlight into electricity through photovoltaic cells or concentrated solar power. The deployment of solar energy is expanding rapidly in response to climate change imperatives and declining costs. Solar power offers substantial greenhouse gas emission reductions compared to fossil fuels, contributing indirectly to biodiversity conservation through climate change mitigation. A comprehensive review of 54 studies on solar PV biodiversity impacts reveals significant knowledge gaps and methodological inconsistencies. Approximately 76% of studies focus on the operational stage of solar PV systems, particularly the effects of land use. Research suggests that solar PV sites can negatively impact biodiversity when installed in natural areas but may offer benefits when sited on degraded or low-biodiversity areas, with 69% of studies focusing on biodiversity-conscious planning and maintenance showing that this could further enhance onsite biodiversity levels[36]. Research findings on the biodiversity impacts of solar PV installations vary considerably. Analysis of the scientific literature indicates that the biodiversity effects of solar PV systems remain inconclusive, with some studies reporting positive effects on biodiversity and others documenting negative impacts. Land-use-related biodiversity impacts are the most studied aspect, while other life-cycle stages (raw material extraction, manufacturing, and end-of-life disposal) are less understood despite their potential to contribute to

biodiversity loss through pollution, habitat loss, and climate change[37].

Taxonomic coverage in solar PV biodiversity research is uneven. Most studies focus on plants, birds, mammals, insects, and soil organisms, while amphibians and reptiles are severely underrepresented. This imbalance is significant given that insects and soil organisms constitute the majority of described species but receive limited research attention. Geographic coverage is also uneven, with China (where most solar PV capacity is installed) being underrepresented in biodiversity-focused studies, while Australia and Brazil—countries with unique biodiversity and significant solar energy potential—are completely missing from the literature[38].

4.2. Wind Energy

Wind energy has both shared and unique biodiversity effects in terrestrial and marine realms. Onshore wind has been documented to alter species behavior in the vicinity of turbines and cause wildlife mortality from collisions. Offshore wind structures, in contrast, can benefit ecosystems by creating substrate for reef-building organisms to colonize; wind facilities are also closed to fishing, which can turn development areas into de facto marine protected areas[39]. A central issue raised by research on both onshore and offshore wind is the need for projects to establish meaningful mitigation plans, including the avoidance of harmful effects, minimization of mortality, and offsetting of biodiversity loss elsewhere. Strategic siting avoiding establishment in key biodiversity areas, areas requiring forest loss, or along migratory flyways is expected to be an important approach to balancing biodiversity trade-offs[40].

4.3. Hydropower and Ecological Concerns

Hydropower, as a mature renewable technology, has received substantial scientific attention regarding its biodiversity effects. Large-scale hydropower projects cause significant habitat fragmentation, alter river flow regimes, and disrupt fish migration. Small-scale hydropower may have lower impacts but still requires careful environmental assessment. The trade-offs between

hydropower's climate benefits and its local biodiversity costs must be carefully evaluated in energy planning[41].

4.4. Geothermal Energy

Geothermal energy harnesses heat from the Earth's interior for electricity generation and direct heating. While geothermal has a relatively small land-use footprint compared to solar or wind, development can affect local ecosystems through land disturbance, water use, and emissions of trace gases. Biodiversity impacts are typically localized but can be significant in sensitive geothermal areas[42].

4.5. Bioenergy and Biomass

Biomass is a versatile renewable resource with applications spanning bio-based products, biogas technology, electricity generation, biodiesel, feedstock processing, and fuel ethanol. The bioenergy industry faces many obstacles, including climate change effects, economic fluctuations, government policies, knowledge gaps, land-use changes, and stakeholder engagement. At the core of bioenergy assessments is the biomass resource inventory, which estimates the availability of feedstocks like agricultural residues, forest biomass, energy crops, and waste materials. The seasonal and sporadic availability of biomass, particularly harvest residues in small-scale farming, poses significant challenges for consistent bioenergy operations[43].

4.6. Green Hydrogen

Green hydrogen, produced through electrolysis using renewable electricity, represents an emerging clean energy carrier. While hydrogen itself produces no emissions when used, its production

requires significant electricity and water resources. The biodiversity implications are primarily indirect, through land-use requirements for renewable energy generation and water consumption[44].

4.7. Mining Impacts and Material Requirements

The construction of wind, hydropower, and solar infrastructure requires minerals including rare earth elements and bulk materials such as steel, aggregates, and cement. The land clearing required for mining these minerals is an important concern for biodiversity and human wellbeing, particularly given the extent to which mining occurs on Indigenous peoples' lands. The escalating rate of demand for these materials and currently insufficient efforts to minimize biodiversity impacts are likely to undermine climate and biodiversity goals. Responsible sourcing of minerals, strategic site selection, and operational scheduling to reduce harms to seasonally sensitive species are potential paths forward[45].

4.8. Strategies for Biodiversity-Friendly Renewable Energy Deployment

Despite overall global progress, the renewable energy transition is inconsistent across regions. The existence of animal fatalities is being used by renewable energy antagonists to stall progress; the fact that these technologies have downsides for biodiversity should not be used as an excuse to halt their development altogether. Rather, now is the time to collect robust data, identify and deploy evidence-based mitigation measures, and model how the effects of varying technologies compare to the counterfactual of continued fossil fuel reliance[46].

Table 3. Applications, Advantages, Limitations, and Potential Ecological Risks of Renewable-Energy Technologies [46], [47], [48].

Technology	Applications	Advantages for Biodiversity	Limitations	Ecological Risks
Solar PV	Electricity generation	Reduced emissions vs. fossil fuels can be sited on degraded land	Land use, material requirements	Habitat loss from large installations; mineral extraction impacts

Wind (Onshore)	Electricity generation	Reduced emissions	Land use, wildlife collisions	Bird/bat mortality, habitat fragmentation, behavioral disturbance
Wind (Offshore)	Electricity generation	Reduced emissions; reef creation	Construction disturbance	Underwater noise; seabird collisions; cable installation impacts
Hydropower	Electricity generation	Reduced emissions	Large land/water requirements	Habitat fragmentation; flow alteration; fish migration disruption
Geothermal	Electricity/heating	Small land footprint	Limited suitable locations	Local habitat disturbance; water use; trace gas emissions
Bioenergy	Electricity, fuel, products	Renewable resources; waste utilization	Land use and water requirements	Habitat conversion: biodiversity loss from feedstock production
Green Hydrogen	Fuel, industry	Zero-emission fuel	High energy/water requirements	Indirect land-use impacts: water consumption
Material Mining	Technology manufacturing	Enables renewable transition	Land disturbance, pollution	Habitat destruction; water contamination; Indigenous land impacts

5. Environmental Biotechnology for Conservation

Environmental biotechnology leverages biological systems to address environmental challenges, offering sustainable alternatives to conventional remediation and restoration approaches. Recent developments in synthetic biology, AI-assisted waste management, engineering of microbial consortia, and circular bio-economy models have enhanced the efficiency of remediation processes[49].

5.1. Bioremediation of Contaminated Ecosystems

Bioremediation uses microorganisms to degrade or transform pollutants into less harmful substances. Various in situ and ex situ remediation techniques—including bioaugmentation, biostimulation, biosparging, land farming, composting, and bioreactor techniques—are highly efficient for the degradation of hydrocarbons, dyes, pharmaceutical compounds, heavy metals, volatile organic compounds, and plastic pollutants. A major method of cleaning polluted sites,

bioremediation involves the use of microorganisms that break down different harmful pollutants into harmless substances, thereby restoring ecosystem sustainability. Plants also play a role in rebuilding ecosystems by removing polluted substances through phytoremediation. Other biotechnological approaches such as biodegradation, biofiltration, microplastic degradation, enzymatic engineering, metabolic engineering, and biomonitoring not only degrade harmful pollutants but also control environmental pollution by monitoring contaminants[50]. The practical application of these strategies for diesel-contaminated, heavy metal-infested, and climate change-affected soils has been demonstrated through case studies from various regions. However, bioremediation technologies also suffer from several limitations: slow remediation rates, environmental risks, and regulatory issues. Further developments involve implementation of multi-omics techniques, genetic engineering, policy enforcements, and community participation to improve the scalability and sustainability of the approach[17].

5.2. Phytoremediation

Phytoremediation uses plants to remove, degrade, or stabilize environmental contaminants. Plants can extract heavy metals, degrade organic pollutants, and stabilize contaminated soils. Recent developments in CRISPR-based genome engineering have made it possible to precisely manipulate metal transporters, detoxification enzymes, and stress-response pathways in plants, opening up new possibilities to improve phytoremediation efficiency[51].

5.3. Microbial Remediation

Microbial remediation employs specific microorganisms to degrade environmental contaminants. Halotolerant plant growth-promoting rhizobacteria exhibit important roles in pollutant mineralisation through different metabolic pathways. Engineered microbial consortia can achieve synergistic degradation of complex pollutant mixtures that single strains cannot effectively process. Microbial genera such as *Pseudomonas*, *Bacillus*, *Alcanivorax*, *Aspergillus*, and *Trametes* exhibit important roles in pollutant mineralisation, transformation, and detoxification through different metabolic pathways and enzyme systems[52].

5.4. Biosorption and Bioaccumulation

Biosorption uses biological materials to remove pollutants from solutions through passive binding, while bioaccumulation involves active uptake by living organisms. These approaches are particularly effective for heavy metal removal from contaminated water and industrial effluents. Recent advances in metabolic engineering and synthetic biology have opened new possibilities to enhance biosorption capacity and selectivity through precise manipulation of metal transporters[53].

5.5. Wastewater Treatment Using Microorganisms and Algae

Biological wastewater treatment employs microorganisms to degrade organic pollutants and remove nutrients. Activated sludge processes, biofilm reactors, and algal-based systems provide cost-effective treatment. Algae, in particular, offer

dual benefits of nutrient removal and biomass production for bioenergy. Bioreactors utilizing engineered microorganisms for carbon sequestration can also purify water and generate bioenergy[54].

5.6. Microbial Technologies for Soil Restoration

Soil restoration technologies use microorganisms to improve soil health, structure, and fertility. Microbial inoculants can enhance nutrient cycling, degrade soil contaminants, and suppress plant pathogens. These approaches support the restoration of degraded agricultural lands and post-industrial sites. The combination of engineered microorganisms with soil microbiome engineering offers synergistic benefits for soil restoration[55].

5.7. Integrated Biotechnology Systems

The convergence of biotechnologies from different fields offers synergistic benefits, leading to innovative solutions that address multiple environmental issues simultaneously. Integrating biotechnologies such as synthetic biology, genomics, and bioremediation can result in holistic solutions.

Multifunctional biotechnological systems can be developed to address several environmental challenges at once. For instance, bioreactors utilizing engineered microorganisms for carbon sequestration can also purify water and generate bioenergy, reducing atmospheric CO₂ while improving water quality and generating renewable energy. Furthermore, platforms integrating data from biosensors, genomic databases, and remote sensing technologies can provide comprehensive environmental monitoring and management solutions, enabling real-time data integration and analysis that supports informed decision-making and adaptive management strategies[14].

5.8. Genome-Based Approaches for Threatened Species

Genomic technologies support conservation through population genetic analysis, genetic rescue, and assisted gene flow. Whole-genome sequencing reveals genetic diversity, inbreeding, and adaptive potential in threatened populations.

Conservation genomics informs management decisions regarding translocations, captive breeding, and habitat restoration. However, ecological risks, ethical concerns, and legal issues surrounding genetic manipulation must be addressed[56].

5.9. Biotechnology-Assisted Restoration of Degraded Ecosystems

Biotechnology applications for ecosystem restoration include the use of engineered

microorganisms and plants to accelerate recovery processes. Problems associated with scale-up, environmental variability, pollutant complexity, cost-effectiveness, and incomplete mineralization hinder practical application in field conditions. Nevertheless, integrated approaches combining biotechnology with other restoration methods offer promising pathways for ecosystem recovery[57].

Table 4. Environmental Biotechnology Approaches for Ecosystem Restoration and Pollution Remediation [58], [59], [60].

Approach	Mechanism	Target Contaminants	Applications	Advantages	Limitations
Bioremediation	Microbial degradation	Hydrocarbons, dyes, pharmaceuticals, plastics	Soil, water, sediment remediation	Cost-effective, sustainable	Slow rates, incomplete degradation
Phytoremediation	Plant uptake/transformation	Heavy metals, organics	Soil and water cleanup	Aesthetic, low cost	Slow, biomass disposal issues
Microbial Remediation	Specific microbial activity	Heavy metals, organics	Contaminated sites	Targeted, adaptable	Environmental variability
Biosorption	Passive binding	Heavy metals	Wastewater treatment	Efficient, low cost	Regeneration requirements
Algal Remediation	Nutrient uptake, pollutant removal	Nutrients, heavy metals	Wastewater treatment	Biomass co-benefits	Light requirements, harvesting
Bioreactors (MFCs)	Microbial electricity generation	Organic waste	Waste treatment, energy production	Energy generation, waste reduction	Scale-up challenges
Synthetic Biology	Engineered organisms	Complex pollutants	Advanced remediation	Tailored solutions	Ecological risks, regulation
Genomic Approaches	Genetic analysis, editing	Genetic conservation	Threatened species	Precision, targeted	Ethical concerns

6. Green Technologies for Sustainable Agriculture

6.1. Precision Agriculture

Precision agriculture uses sensor-based, data-driven approaches to optimize crop management, reduce inputs, and maintain productivity. Technological advancements allowing for

individual plant-level management can address agricultural biodiversity challenges. Precision agriculture can foster cropland weed diversity and protect endangered species by enabling selective management that leaves beneficial species in the field. Weed diversity plays an important role in the functioning of agroecosystems, and a number of

endangered and threatened plant species occur as weeds in arable fields and field boundaries. Agricultural intensification has imposed negative consequences on weed diversity in general and on the survival of endangered and threatened plant species in particular. While nonchemical weed management methods and economic threshold-based approaches are touted to improve weed diversity, they are either ineffective or insufficient for this purpose; long-term economic consequences and the risk of weed adaptation are major concerns[61].

A plant functional trait-based approach to promoting weed diversity—one that considers a plant's ecosystem service potential and competitiveness with the crop—has been proposed. This approach has tremendous potential for weed diversity conservation in commercial production systems, but field implementation has been limited due to our inability to selectively control weeds at the individual-plant level. However, recent advancements in computer vision, machine learning, and site-specific weed management technologies may allow for accurate elimination of unwanted plants while retaining important ones. A novel framework for utilizing precision agriculture for conservation of cropland weed diversity ranks control priority on an individual-plant basis by integrating intrinsic weed trait values with field infestation characteristics, while management thresholds are tailored to specific goals and priorities. Government policies can steer implementation through appropriate incentives to farmers and industry, while outreach and educational programs need to be developed to disseminate the importance of biodiversity in agroecosystems[62].

6.2. Smart Irrigation Systems

Smart irrigation systems optimize water use through sensor-based monitoring of soil moisture, weather conditions, and crop water requirements. These systems reduce water waste, prevent nutrient leaching, and maintain soil health. Precision irrigation supports sustainable agriculture while conserving freshwater resources[63].

6.3. Remote Sensing for Crop and Soil Management

Remote sensing provides data on crop health, nutrient status, soil properties, and pest infestations. Satellite and drone-based imagery enable targeted management interventions, reducing chemical inputs and improving resource efficiency. Optical, multispectral, and thermal sensors capture different aspects of crop and soil condition[64].

6.4. Agricultural Drones and Robotics

Drones and agricultural robots enable precise application of inputs, targeted pest control, and autonomous field operations. These technologies reduce labor requirements, minimize soil compaction, and enable site-specific management. However, high costs and technical expertise requirements limit adoption in smallholder farming systems[65].

6.5. Biofertilisers and Microbial Inoculants

Biofertilisers use beneficial microorganisms to enhance nutrient availability and plant growth. Nitrogen-fixing bacteria, phosphate-solubilising organisms, and plant growth-promoting rhizobacteria provide sustainable alternatives to synthetic fertilisers. Biofertilisers support soil health, reduce chemical inputs, and maintain agricultural productivity. The combination of genetically modified crops with bioinoculants has been implemented in regions facing severe water scarcity, leading to improved crop yields and greater resilience under challenging environmental conditions[66].

6.6. Biopesticides and Biological Control

Biopesticides derived from natural sources provide alternatives to synthetic pesticides. Biological control using natural enemies suppresses pest populations while maintaining beneficial insects. These approaches reduce chemical contamination of agricultural landscapes, supporting farmland biodiversity. However, the effectiveness of biocontrol agents can be variable and dependent on environmental conditions[67].

6.7. Climate-Resilient Agriculture

The development of climate-resilient agricultural systems combines gene editing with soil microbiome engineering. Using CRISPR/Cas9 technology, scientists have precisely altered plant genomes to enhance traits like drought resistance and salt tolerance. These genetically modified crops are paired with bioinoculants—beneficial soil microbes that improve soil health, water retention, and nutrient availability. This combined approach has been implemented in regions facing severe water scarcity, leading to improved crop yields and greater resilience under challenging

environmental conditions[68].

6.8. Vertical Farming and Controlled-Environment Agriculture

Vertical farming and controlled-environment agriculture produce food in stacked layers within climate-controlled facilities. These systems use less land and water than conventional agriculture, reduce transportation emissions, and eliminate pesticide use. However, high energy requirements and capital costs limit their adoption, and biodiversity benefits depend on land-sparing effects that must be verified[69].

Table 5. Green Technologies for Sustainable Agriculture and Their Effects on Soil, Water, and Biodiversity[69], [70], [71], [72]

Technology	Application	Soil Benefits	Water Benefits	Biodiversity Effects
Precision Agriculture	Input optimization	Reduced compaction, targeted nutrient application	Reduced runoff, efficient irrigation	Supports weed diversity, protects non-target species
Smart Irrigation	Water optimization	Reduced leaching	Water conservation, reduced runoff	Maintains aquatic habitat, reduces water extraction
Biofertilizers	Nutrient provision	Improved soil health, reduced chemical inputs	Reduced nutrient pollution	Supports soil biodiversity, reduces chemical impacts
Biopesticides	Pest control	Reduced soil contamination	Reduced water contamination	Protects beneficial insects, reduces non-target effects
Crop Rotation/Diversity	Pest/disease management	Improved soil structure, nutrient cycling	Reduced chemical runoff	Supports habitat diversity, pollinator communities
Agroforestry	Integrated production	Soil conservation, carbon sequestration	Water infiltration, quality improvement	Provides wildlife habitat, corridors
Conservation Tillage	Soil management	Reduced erosion, organic matter retention	Reduced sedimentation	Supports soil organisms, ground-nesting species
Drones/Robotics	Field operations	Reduced compaction	Precise application	Enables selective management, reduces chemical use
Vertical Farming	Controlled production	Land sparing	Water-efficient	Potential land sparing, reduced field impacts

GM Crops + Bioinoculants	Climate- resilient production	Improved health	soil	Reduced needs	water	Variable, requires careful assessment
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7. Green Technologies for Water Conservation and Aquatic Ecosystems

Advanced wastewater treatment removes contaminants beyond conventional primary and secondary treatment. Technologies including membrane filtration, advanced oxidation, and nutrient removal protect water quality and aquatic ecosystems. Treatment processes must address emerging contaminants including pharmaceuticals, personal care products, and microplastics. Membrane technologies including microfiltration, ultrafiltration, nanofiltration, and reverse osmosis provide effective barriers to pollutants. Membranes remove suspended solids, pathogens, and dissolved contaminants, enabling water reuse and protecting aquatic ecosystems. However, membrane fouling, energy consumption, and brine disposal pose challenges that require ongoing research[73].

Constructed wetlands use natural processes—including vegetation, soils, and microbial communities—to treat wastewater and stormwater. These systems provide cost-effective treatment while creating wildlife habitat and supporting biodiversity. Constructed wetlands offer dual benefits of water quality improvement and habitat provision, making them valuable for integrated water management. Biological purification employs microorganisms and aquatic plants to remove pollutants from water. Algal remediation, fungal-based remediation, and engineered microbial systems treat agricultural runoff, industrial effluents, and municipal wastewater. These approaches provide sustainable, low-cost alternatives to energy-intensive treatment methods[74]. Desalination provides freshwater from seawater and brackish sources but requires substantial energy and has brine disposal challenges. Energy-efficient desalination technologies including forward osmosis, membrane distillation, and electrochemical approaches reduce energy requirements and environmental impacts. Renewable energy-

powered desalination offers potential for sustainable water supply in water-scarce regions. Smart water management integrates sensors, data analytics, and automation to optimize water use and quality. Real-time monitoring enables early detection of pollution events, efficient irrigation, and optimized treatment operations. IoT-based monitoring and predictive analytics support adaptive water resource management[75].

Emerging contaminants including pharmaceuticals, microplastics, and per- and polyfluoroalkyl substances (PFAS) pose growing threats to aquatic ecosystems. Advanced detection methods including mass spectrometry and biosensors enable monitoring at trace concentrations. Removal technologies including advanced oxidation, adsorption, and membrane filtration address these contaminants, though comprehensive solutions remain under development. Freshwater biodiversity conservation benefits from monitoring technologies including eDNA analysis, acoustic monitoring, and remote sensing. eDNA has revolutionized aquatic biodiversity assessment, enabling detection of rare, cryptic, or difficult-to-observe species without direct sampling. Habitat restoration technologies address river connectivity, flow regimes, and riparian zones. Water quality monitoring and pollution control protect freshwater species and ecosystems. Marine monitoring technologies include satellite remote sensing, autonomous underwater vehicles, acoustic telemetry, and environmental DNA. Coral reef monitoring uses high-resolution imagery, photogrammetry, and automated classification. Marine pollution detection addresses oil spills, plastic accumulation, and chemical contamination. The biodiversity effects of deep-sea mining, which is escalating, require monitoring that is more challenging than for terrestrial mining[76], [77].

8. Sustainable Waste Management and Circular Economy Technologies

8.1. Principles of the Circular Economy

With increasing pressure on global resources and the urgent need for climate action, the concept of "waste" is undergoing a major transformation. No longer viewed as the endpoint of consumption, waste is now being redefined as a valuable starting point within a circular economy. Science-driven strategies convert waste into critical materials, renewable energy, and economic value. The circular economy aims to eliminate waste through continuous resource use, material recovery, and regenerative design. Principles include designing for durability, reuse, repair, and recycling; maintaining product value across life cycles; and decoupling economic activity from resource consumption. Green technologies enable circular economy transitions through improved material recovery, waste treatment, and product design[78].

8.2. Waste-to-Energy Technologies

Waste-to-energy technologies convert waste materials into electricity, heat, or fuel. Combustion, gasification, and pyrolysis reduce waste volume while generating energy. Anaerobic digestion and microbial fuel cells (MFCs) produce energy from organic waste streams. The integration of MFCs and bioremediation technologies provides multiple benefits: waste reduction, energy production, and wastewater treatment[79].

8.3. Anaerobic Digestion and Microbial Electrolysis Cell Integration

Anaerobic digestion breaks down organic waste in the absence of oxygen, producing biogas (methane) and digestate. Biogas can generate electricity, heat, or fuel, while digestate provides nutrient-rich soil amendment. However, conventional AD systems often face challenges such as over-acidification, which limits efficiency and stability. To overcome these limitations, researchers have developed a hybrid microbial electrolysis cell-anaerobic digestion (MEC-AD) system. This system integrates electrodes and low-voltage inputs to enhance microbial activity, achieving a 65.4% increase in methane production while improving

system stability. The research highlights a functional partitioning mechanism within the system, where bio-anodes drive methane production, bio-cathodes stabilize the process by reducing acid accumulation, and suspended microbes facilitate the breakdown of complex organic matter. This advancement significantly improves the efficiency and reliability of biomass-to-energy conversion[80].

8.4. Composting and Biological Waste Treatment

Composting converts organic waste into stable soil amendments through aerobic decomposition. Large-scale composting and in-vessel systems process municipal, agricultural, and industrial organic waste. Biological waste treatment reduces landfill disposal, recovers nutrients, and improves soil health. Knowledge gaps regarding optimal conditions and end-product quality limit broader adoption[81].

8.5. Plastic Circularity

Plastic waste continues to be a global environmental concern, and traditional reduction strategies alone are no longer sufficient to tackle its complexity. Research emphasizes the need to transition from linear consumption models to closed-loop systems. This work advocates for "intelligent design" at the production stage and the adoption of advanced upcycling technologies to convert plastic waste into high-value materials, minimizing environmental impact while enhancing long-term resource efficiency and industrial sustainability[82].

8.6. Biodegradable and Bio-based Materials

Biodegradable materials derived from biological sources offer alternatives to conventional plastics. Polylactic acid (PLA), polyhydroxyalkanoates (PHAs), and starch-based materials degrade under appropriate conditions. Bio-based materials reduce reliance on finite resources and can be produced from renewable feedstocks. However, biodegradability depends on environmental conditions and may not occur in landfills or marine environments[83].

9. Green Technologies for Climate Change Mitigation and Adaptation

Climate change interacts with other stressors to drive biodiversity loss across all ecosystems. Rising temperatures shift species ranges, disrupt ecological interactions, and reduce ecosystem resilience. Extreme weather events—droughts, floods, and storms—cause acute biodiversity impacts. Climate change also exacerbates habitat fragmentation, pollution effects, and invasive species spread. Addressing climate change is therefore critical for biodiversity conservation[84]. Carbon capture, utilization, and storage (CCUS) technologies capture CO₂ from industrial sources and either utilize it or store it permanently. Post-combustion capture, pre-combustion capture, and oxyfuel combustion are established approaches. Utilization pathways produce chemicals, fuels, or building materials from captured CO₂. Geologic storage in depleted oil and gas reservoirs or saline aquifers provides long-term sequestration. CCUS faces challenges including high costs, energy penalties, and uncertain long-term storage integrity. Direct air capture (DAC) removes CO₂ directly from ambient air using chemical sorbents or membranes. Unlike point-source capture, DAC can address diffuse emissions and historical CO₂. However, high energy requirements and costs limit current deployment[85]. DAC siting must consider land use, water consumption, and energy infrastructure. The integration of DAC with renewable energy offers potential for net-negative emissions. Nature-based solutions harness ecosystem processes for carbon sequestration. Forest conservation and restoration, soil carbon management, and blue carbon (mangroves, seagrasses, salt marshes) provide significant mitigation potential. Nature-based approaches offer co-benefits for biodiversity, water quality, and local livelihoods. However, carbon accounting, permanence, and additionality concerns must be addressed. Remote sensing-based habitat mapping provides transparent evidence to guide restoration and track progress towards climate and biodiversity goals[86].

Biochar produced through pyrolysis of biomass sequesters carbon in stable form for centuries. Biochar application to soil improves fertility, water

retention, and crop yields while reducing greenhouse gas emissions. Feedstock availability, production costs, and quality control pose challenges. The integration of biochar with bioenergy production offers synergistic climate benefits but must consider land-use trade-offs. Reforestation and forest restoration benefit from advanced technologies for site selection, species choice, and monitoring. Precision planting and data mining improve the prospects of reforestation. Drone-based seed dispersal and automated seedling monitoring support large-scale restoration efforts. Technologies like satellite monitoring and AI provide tools to support real-time forest trackers and enable faster response to forest fires and pests[32].

10. Green Infrastructure and Sustainable Urban Ecosystems

Green buildings incorporate environmental considerations throughout design, construction, and operation. Features include energy efficiency, water conservation, sustainable materials, and indoor environmental quality. Green building certification systems—LEED, BREEAM, and similar—promote environmental performance. Green buildings reduce resource consumption and provide habitat through rooftop and site design. Green roofs vegetate building surfaces, reducing stormwater runoff, providing insulation, and creating wildlife habitat. Vertical gardens or green walls bring vegetation to building facades. These features support urban biodiversity, reduce urban heat island effects, and improve air quality. Green roofs provide habitat for birds, insects, and other taxa in urban environments. Urban forests encompass all trees in urban areas—parks, street trees, and natural areas. Urban forests provide habitat, reduce heat island effects, improve air quality, and support human wellbeing. Urban forest management includes tree inventory, maintenance, and expansion planning. Emerging technologies support urban forest monitoring and management[87].

11. Integrated One Health and Ecosystem Sustainability Perspective

Biodiversity, environmental health, and human health are inextricably linked through ecosystem services, disease dynamics, and environmental quality. Biodiversity loss can increase disease transmission, reduce nutritional security, and diminish the mental health benefits of nature. The One Health approach recognises these interconnections, requiring integrated solutions that address health at the human-animal-environment interface. Zoonotic disease risks are influenced by biodiversity loss, habitat fragmentation, and wildlife trade. Technologies for wildlife health surveillance including pathogen detection and disease modelling support early warning and outbreak prevention. Environmental DNA can detect pathogens in water and wildlife populations. Habitat monitoring can identify areas of high disease spillover risk[88].

Environmental pollution contributes to antimicrobial resistance through selection pressure from antibiotics, disinfectants, and heavy metals. Pollution control technologies reduce the environmental dissemination of antimicrobials and resistance genes. Bioremediation and wastewater treatment remove pharmaceuticals and disinfectants before environmental release. Emerging developments in synthetic biology enhance the efficiency of remediation processes[89].

18. Conclusions

This review has examined the diverse array of green technologies available for biodiversity conservation and environmental sustainability, revealing both unprecedented opportunities and significant challenges. The major technological opportunities include advanced monitoring systems that enable comprehensive biodiversity assessment at unprecedented scales, bioremediation approaches that can restore contaminated ecosystems, precision agriculture that reduces environmental impacts while maintaining productivity, and renewable energy technologies that address climate change. These technologies, when strategically deployed, can contribute substantially to addressing the drivers

of biodiversity loss and achieving sustainability goals. However, green technologies are not a panacea. Environmental and socioeconomic limitations including high costs, technical expertise gaps, e-waste generation, and the ecological impacts of renewable energy infrastructure—require careful consideration. The biodiversity outcomes of renewable energy deployment vary markedly with where, how, and which technologies are deployed. The mining of materials for renewable technologies is associated with large-scale land conversion and currently insufficient efforts to minimize biodiversity impacts. Strategic siting, the mitigation hierarchy, and evidence-based mitigation measures are essential for balancing biodiversity trade-offs. The need for interdisciplinary approaches is paramount. No single technology or discipline can address the complexity of biodiversity loss and environmental degradation. Integration across ecology, engineering, social science, and policy is essential for effective solutions. Platforms integrating data from biosensors, genomic databases, and remote sensing technologies enable comprehensive environmental monitoring and management, supporting more informed decision-making and adaptive management strategies.

Policy, investment, and equitable technology access are critical for realizing the full potential of green technologies. Governments must provide regulatory frameworks, incentives, and investment for green technology deployment. International cooperation is needed for technology transfer and capacity building in developing countries that harbor the greatest biodiversity. The efficient deployment of green technologies requires sound policy environments, financial backing, and multiple stakeholder engagements. The future transition toward biodiversity-positive and climate-resilient technological systems requires rethinking how technology is developed and deployed. Biodiversity-positive technologies—designed to benefit biodiversity explicitly—represent a paradigm shift from simply reducing harm to actively promoting conservation. The circular bioeconomy and zero-waste systems offer pathways for integrating economic development with environmental sustainability. The evolution of

green technologies and their integration into overall environmental and economic policies will shape the future of conservation.

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All authors Contributed equally

Declaration of Competing Interest

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