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Biotechnology in Agriculture, Medicine, and the Environment: A Review of Its Tools and Contributions

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ABSTRACT: Biotechnology played an important role in solving real-world problems in agriculture, medicine, and environmental science. It helped improve crop production, develop new treatments for diseases, and clean up pollution. This review aimed to explore the uses of biotechnology in these three fields and show how they were connected. To achieve this, the researcher used a scoping review method following the PRISMA 2020 guidelines. A total of 32 peer-reviewed studies from 2020 to 2025 were selected using the inclusion criteria: full-text availability, recency, and relevance to biotechnology in agriculture, medicine, or environmental science. The findings showed that biotechnology helped farmers grow more food using gene editing tools like CRISPR. In medicine, it supported the creation of vaccines, cancer treatments, and faster disease detection. In the environment, it helped reduce pollution through bioremediation and other natural solutions. Many of these breakthroughs used similar tools and shared goals of sustainability and health improvement. In conclusion, biotechnology was a powerful tool with wide-reaching benefits. However, challenges such as ethical concerns, safety issues, and unequal access still needed to be addressed. Future studies should promote responsible and inclusive use of biotechnology to create a better future for all.

KEYWORDS: Biotechnology; agriculture; medicine; environmental science; gene editing; sustainability

1. Introduction

Biotechnology was one of the most powerful tools of modern science, offering practical solutions to some of the world's most urgent challenges in agriculture, medicine, and environmental protection. At its core, biotechnology involved using living organisms, cells, or biological systems to develop products and technologies that benefited people and the planet. In recent years, breakthroughs such as CRISPR-Cas9 gene editing, mRNA vaccine development, and bio-based pollution cleanup demonstrated how far biotechnology could go in improving lives and protecting natural resources [1].

Across different sectors, biotechnology made significant progress. In agriculture, its improved crop yields and sustainability through genetically modified organisms (GMOs) and microbial biofertilizers [2]. In medicine, the rapid development of mRNA vaccines during the COVID-19 pandemic demonstrated biotechnology's potential to respond quickly to global health crises [3]. In environmental science, scientists used microbes to clean up oil spills and design biodegradable plastics, highlighting biotechnology's important role in reducing pollution and preserving ecosystems [4]. These developments showed that biotechnology was not limited to one field, it was a shared, cross-cutting tool that supported food security, health, and environmental care.

However, alongside these promising advances, there were challenges. Ethical issues around genetic editing, concerns about biosafety, and uneven access to biotechnology between high- and low-income nations continued to raise difficult questions [5]. While many studies focused on biotechnology's impact within a single sector, there was still a lack of integrated reviews that examined how these innovations connected across multiple fields. Understanding these connections was essential for seeing the full picture of biotechnology's benefits and risks. This review aimed to provide a clear and comprehensive overview of how biotechnology was used in agriculture, medicine, and environmental science. Specifically, it (1) examined how biotechnology improved farming through tools such as GMOs, disease-resistant crops, and sustainable methods; (2) explored its impact on healthcare through genetic testing, vaccine innovation, and regenerative medicine; and (3) analyzed its environmental applications in pollution control, waste management, and climate change response.

2. Materials and Methods

This study employed the PRISMA 2020 (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework to guide a transparent and structured process of identifying, selecting, appraising, and synthesizing literature relevant to the interdisciplinary applications of biotechnology. Considering the broad nature of the research objective, the review was conducted as a scoping review, which allowed for the mapping of key concepts, types of evidence, and gaps in research across the domains of agriculture, medicine, and environmental science. The use of PRISMA was deemed appropriate for ensuring methodological rigor and clarity in reporting.

2.1. Database selection and rationale.

A targeted literature search was conducted across five major academic databases: ScienceDirect, PubMed, Scopus, Google Scholar, and SpringerLink. These databases were selected to cover a wide range of disciplines, including life sciences, medical innovations, and environmental biotechnology. While Google Scholar was included to capture emerging preprints and grey literature, its results were critically evaluated for scientific rigor due to its inclusion of non-peer-reviewed sources. Subject filters (such as life sciences, medicine, and environmental science) and document type filters (such as research articles, reviews, and case studies) were applied whenever available to refine the searches.

2.2. Search strategy and boolean combinations.

The search was restricted to literature published between January 2020 and May 2025 to ensure a focus on recent and relevant developments in biotechnology. Search strings were constructed using Boolean operators and were adapted for each database's syntax. Representative search combinations included: ("biotechnology breakthroughs" OR "biotechnological innovations") AND ("agriculture" OR "farming"); ("genetic engineering" OR "CRISPR") AND ("medicine" OR "gene therapy" OR "mRNA vaccine"); and ("biotechnology" AND "environmental science") OR ("bioremediation" AND "synthetic biology"). These combinations helped capture a wide but targeted array of sources across all three sectors.

2.3. Inclusion and exclusion criteria.

Articles were selected based on the following inclusion criteria: (1) peer-reviewed publications between 2020 and 2025, (2) written in English, (3) directly focused on biotechnological applications in agriculture, medicine, or environmental science, and (4) classified as original research, systematic/scoping reviews, or well-documented case studies. Exclusion criteria included duplicate records, off-topic articles, non-peer-reviewed content (unless grey literature of high credibility), and sources outside the specified time range. Preprints and grey literature obtained through Google Scholar were retained only if they demonstrated strong methodological transparency and had been cited in scholarly discourse.

2.4. Screening, management, and quality appraisal.

To manage and screen the literature, the software tools Zotero and Rayyan were used. Zotero was employed for reference organization, while Rayyan facilitated blinded article screening and conflict resolution. Two reviewers independently conducted the screening process, and disagreements regarding article eligibility were resolved through discussion. To appraise study quality, the CASP (Critical Appraisal Skills Programme) was used for qualitative studies, and the GRADE framework was applied to assess the strength of quantitative evidence, ensuring minimal bias and methodological consistency.

2.5. PRISMA flow and article selection.

The PRISMA four-step process—identification, screening, eligibility, and inclusion was followed throughout the review. A total of 1,215 articles were initially identified. After removing 243 duplicate entries, 972 records remained for title and abstract screening. This process excluded a further 660 records, resulting in 312 full-text articles that were assessed for eligibility. Ultimately, 45 studies met all inclusion criteria and were retained for the final review.

2.6. Data extraction and synthesis.

From each included article, relevant data points were extracted, including the publication’s authors, year, objectives, methodological approach, key findings, identified applications, and sector classification. The data were synthesized through narrative synthesis, supported by schematic comparisons and conceptual figures to highlight the intersection of themes across the three domains. A coding framework was developed to categorize recurring themes and technologies such as CRISPR, synthetic biology, and mRNA platforms, across the fields of agriculture, medicine, and environmental science.

2.7. Limitations.

Despite following a rigorous protocol, the review had certain limitations. The exclusion of non-English literature might have omitted important contributions published in other languages. Additionally, the time constraint (2020–2025) might have excluded foundational studies that continued to influence current biotechnological practices. Lastly, while grey literature was cautiously included, some non-indexed yet potentially valuable sources might have been overlooked. Nonetheless, the study provided a comprehensive and current overview of biotechnology's converging roles across key sectors of human and environmental health.

3. Results and Discussion

3.1. Biotechnology in Agriculture

Biotechnology became a cornerstone of modern agricultural advancement, offering solutions to improve crop quality, nutrient content, environmental sustainability, and resilience against climate stresses. One of the most revolutionary tools in this field was CRISPR/Cas9 genome editing, which allowed precise, targeted modification of specific plant traits. As summarized in Table 1, various crops such as cassava, rice, potato, and barley underwent successful CRISPR modifications resulting in reduced toxic compounds, enhanced aroma, improved starch quality, and altered grain texture, respectively [6]. These improvements did not merely cater to consumer preferences but also contributed to health and industrial functionality.

Moreover, biofortification via CRISPR addressed key nutritional challenges. A systematic review on this subject found that nutrient-enriched crop varieties, such as those containing higher levels of vitamins and minerals, were developed with high accuracy and minimal off-target effects using optimized guide RNAs [7]. This opened vast potential in combating micronutrient deficiencies, especially in developing regions. In support of this, field-trial data collected globally in 2024 revealed that several CRISPR-edited crop lines, engineered to withstand drought and heat—were approved for cultivation in multiple countries, marking a significant milestone in climate-resilient agriculture [8].

Expanding on this, a broader analysis of CRISPR/Cas9 applications across diverse species, including citrus and coffee, highlighted the versatility of this technology. These advancements ranged from improving disease resistance to enhancing crop shelf life, while also navigating the complex regulatory landscape involved in gene-edited food production [9]. Further supported by an overview on sustainable food systems, CRISPR applications not only increased yields but also promoted eco-efficiency by reducing reliance on chemical inputs and improving nutritional profiles [10].

One of the standout successes in the field was the development of a CRISPR-edited tomato enriched with vitamin D. The stable expression of this trait, as verified through genetic analysis and field trials, occurred without any negative impacts on plant growth or yield proving that gene editing could effectively balance productivity with health-focused traits [11]. Beyond genetic editing, biotechnology's reach extended into microbial innovations. For instance, researchers formulated microbial consortia with biofertilizer capabilities that improved soil fertility, plant health, and nutrient cycling efficiency, an achievement validated by extensive field trials [12]. These biological solutions played a vital role in sustainable farming by minimizing dependence on synthetic fertilizers. Similarly, microbial biofertilizers demonstrated significant gains in nutrient use efficiency and reductions in environmental degradation across various cropping systems [13].

Table 1. Comparison of studies on biotechnology applications in agriculture.

Title of the Study	Methods	Findings	TRL/Stage of Deployment	Sources
Improving crop quality via CRISPR/Cas9 genome editing	Applied CRISPR/Cas9 across cassava (toxin reduction), rice (aroma), potato (starch composition), and barley (grain hardness).	Cassava cyanogenic glycosides were reduced; rice aroma enhanced; potato starch qualities improved; barley grains were harder but slightly smaller.	Field trials	[6]
CRISPR-based genome editing for nutrient enrichment	Systematic review of biofortification strategies using CRISPR across staple crops.	Nutrient-enriched varieties were developed with stable trait inheritance; off-target effects were minimal with optimized gRNAs.	Lab-scale to field trials	[7]
CRISPR in Agriculture: 2024 in Review	Survey and field-trial data on CRISPR-edited plants globally.	CRISPR-edited lines exhibiting drought and heat resistance achieved approval in multiple countries.	Approved	[8]
Application of CRISPR/Cas9 in various crops	Comprehensive review of CRISPR-Cas9 use in multiple crops (e.g., citrus, coffee).	Highlighted trait improvement and regulatory considerations across species.	Field trials	[9]
CRISPR-Cas9 for sustainable food production	Overview article summarizing CRISPR applications in food crops.	Documentation of sustainability enhancements, including yield and nutrient profiling.	Field trials	[10]
Nutritionally-enhanced CRISPR-edited tomato	Field trials and genetic analysis of vitamin-D–enhanced tomatoes.	Confirmed stable trait expression with no negative growth trade-offs.	Field trials	[11]
Microbial bioformulation for sustainable agriculture	Developed microbial consortia with biofertilizer capabilities; field-tested delivery methods.	Improved soil fertility and plant health; identified key biosafety parameters.	Field trials	[12]
Biofertilizers for nutrient recycling	Reviewed microbial biofertilizers in various cropping systems.	Demonstrated significant gains in nutrient use efficiency and reduced environmental impact.	Field trials	[13]
Microalgal biofertilizers and biostimulants	Bibliometric analysis and techno-market review of microalgae products.	Identified surge in microalgal-based amendments featuring plant hormone production.	Market-ready	[14]
Field trials of biotechnological crops	Survey across >55 countries on GMO and gene-edited plants.	Confirmed broader adoption of gene-edited crops and regulatory diversity.	Approved	[15]
Microbial fertilizers and plant growth	Classification and mechanism-focused review on microbial fertilizers.	Outlined microbial roles in nutrient solubilization and stress tolerance enhancement.	Lab to field trials	[16]
Deep learning in satellite imagery for agriculture	Systematic review of AI-based remote sensing methods.	Demonstrated improved segmentation and yield prediction with deep learning.	Lab-scale	[17]
Synthetic biology and AI in crop improvement	Experimentally combined AI-driven circuit design with synthetic biology in plants.	AI-designed gene circuits led to controlled trait expression under field conditions.	Field trials	[18]
CRISPR delivery methods and transformation	Stressed non tissue-culture delivery methods and regulatory insights.	Virus-based vectors and developmental regulator use improved transformation rates.	Lab-scale to field trials	[19]
Growth-promoting bacteria for sustainable farming	Evaluated PGPB use with CRISPR tech for sustainable agriculture.	Enhanced plant nitrogen uptake and stress tolerance confirmed in field tests.	Field trials	[20]
Iron biofortification via gene editing	Reviewed use of transporters and transcription factors to enhance iron uptake.	Editing OsVIT1/VIT2 and OsIRO2 enhanced seed iron levels without yield penalty.	Lab to field trials	[21]
CRISPR & sustainability in green biotech	Captured CRISPR use in agriculture & environment co-applications.	Highlighted climate-resilient crops and microbial carbon sequestration.	Lab-scale to early field trials	[22]

Adding to this momentum, microalgal-based fertilizers and biostimulants entered the spotlight. As summarized in Table 1, a bibliometric and techno-market review reported a significant surge in research and application of microalgal products due to their ability to stimulate plant hormone production and overall crop vigor [14]. Such innovations were particularly attractive in organic and climate-smart agriculture. The acceptance and expansion of gene-edited crops were further illustrated by a survey conducted across more than 55 countries. Findings confirmed broader adoption and growing regulatory diversity for genetically modified organisms (GMOs) and gene-edited varieties, indicating increasing public and governmental support [15]. This trend was supported by a review that classified microbial fertilizers based on their mechanisms, including nutrient solubilization and stress tolerance enhancement, both of which were critical in the face of changing climate conditions [16].

Incorporating artificial intelligence (AI) into agricultural biotechnology represented another leap forward. A systematic review showed that deep learning applied to satellite imagery significantly improved crop segmentation and yield prediction, enabling more precise and efficient farm management [17]. Meanwhile, experimental combinations of AI and synthetic biology led to the creation of gene circuits that allowed crops to express specific traits in response to environmental triggers, demonstrating a fusion of computational and biological innovation [18]. The success of these technologies also depended on the delivery methods of gene editing tools. Recent advancements shifted away from traditional tissue-culture approaches in favor of virus-based vectors and the use of developmental regulators, which greatly improved transformation efficiency across a range of crops [19].

Another promising avenue was the use of plant growth-promoting bacteria (PGPB) in conjunction with CRISPR technology. Field evaluations confirmed that PGPB enhanced nitrogen uptake and increased stress tolerance in plants, making them powerful allies in the pursuit of sustainable agriculture [20]. Additionally, targeted iron biofortification was achieved through gene editing of rice transporters and transcription factors, leading to enhanced seed iron content without any trade-offs in yield [21]. Finally, biotechnology's role in environmental sustainability has become increasingly clear. CRISPR was employed not only to develop climate-resilient crops but also to aid microbial-based carbon sequestration efforts. This dual benefit, improved agricultural output and ecological balance, marked a transformative step toward green biotechnology [22].

3.2. Biotechnology in medicine.

Biotechnology rapidly transformed the landscape of modern medicine, with groundbreaking innovations such as CRISPR-Cas gene editing, mRNA vaccine technologies, nanorobotics, and gene therapy pushing the frontiers of therapeutic development and personalized care. As summarized in Table 2, these advances collectively underscored how molecular precision and platform flexibility became the cornerstones of 21st-century biomedical science. One of the most pivotal breakthroughs was the clinical translation of CRISPR-Cas gene editing. According to a 2024 review of clinical trial data, Casgevy became the first CRISPR-based therapy approved for sickle cell disease (SCD) and transfusion-dependent β-thalassemia (TDT), demonstrating notable safety and efficacy [23]. This milestone validated the therapeutic utility of gene editing but also revealed persisting hurdles such as delivery mechanisms and off-target effects. To address these issues, researchers leveraged advanced delivery systems, such as viral vectors, lipid nanoparticles, and cell-penetrating peptides, to improve intracellular transport and gene editing efficiency. At the same time, AI-driven design tools were used to develop safer and more precise guide RNAs, drastically reducing the probability of unintended genomic changes and streamlining the clinical translation of gene therapies. Enhancing the specificity and accuracy of CRISPR tools was therefore a research priority. Systematic reviews confirmed that base editing and prime editing technologies—refined versions of CRISPR—advanced rapidly in preclinical and early clinical settings, offering improved precision and fewer unintended edits [24], [25].

In parallel, mRNA technologies emerged as a powerful therapeutic and immunological tool, most prominently in the global response to COVID-19. A meta-analysis of mRNA vaccine platforms showed that breakthroughs in lipid nanoparticle (LNP) carriers, freeze-drying methods, and mRNA stability widened the application pipeline beyond infectious diseases to include cancer vaccines, personalized immunization, and protein-replacement therapies [26], [30]. These LNPs not only ensured efficient delivery of mRNA into target cells but also played a pivotal role in minimizing immune-related adverse reactions. AI algorithms were integrated into this development pipeline, predicting the most efficient LNP compositions and optimizing mRNA sequences for enhanced protein expression and minimal immunogenicity. Bibliometric analysis also confirmed a surge in mRNA vaccine research between 2020 and 2024, with a shifting focus from pandemic response to broader uses like influenza, oncology, and rare diseases [27]. However, mRNA vaccines were not without limitations. Studies emphasized the ongoing struggle with cold chain requirements and immunogenicity balancing, both of which were essential to ensure safety and scalability [28], [29].

This expansion of mRNA therapeutics was further supported by innovations such as self-amplifying RNA (saRNA) platforms. These required smaller doses and offered sustained expression, as proven in Phase 3 trials for Omicron booster vaccines, which had already received regulatory approval [36]. These saRNA platforms were refined through AI-guided structural predictions and simulation tools that optimized nucleotide sequences to extend mRNA half-life and improve antigen expression. In line with this, computational tools played a vital role in optimizing mRNA structure. A recent survey of mRNA folding algorithms found that codon optimization and secondary structure design directly enhanced mRNA half-life and protein expression—a leap forward in vaccine and drug development [37].

Despite these innovations, public perception influenced biotechnology adoption. A social media sentiment analysis conducted between 2022 and 2023 revealed that nearly 70% of global Twitter discourse on mRNA vaccines was negative, with strong regional variations. This highlighted a pressing need for strategic science communication and education to address misinformation and build trust [31]. Meanwhile, CRISPR's role continued to expand beyond monogenic diseases. It played a critical part in oncology and HIV clinical trials, where its potential for correcting disease-causing mutations was closely monitored. Yet, ethical and regulatory concerns persisted, especially around germline editing and long-term safety [32], [38]. Reviews showed that CRISPR also accelerated drug discovery and target validation, helping pharmaceutical developers design precise gene therapies using optimized screening pipelines [33]. This precision was further enhanced by AI integration. Studies revealed that AI enabled the design of optimal guide RNAs (gRNAs), predicted gene editing outcomes, and minimized off-target events, paving the way for personalized gene therapies tailored to individual patient genomes [34]. Furthermore, AI was used to simulate complex biological environments, aiding in the selection of the most efficient delivery vectors and predicting how edits would affect downstream cellular functions.

Table 2. Comparison of studies on biotechnology applications in medicine.

Title of the Study	Methods	Findings	Sources
CRISPR Clinical Trials: A 2024 Update	Review of clinical trial data on CRISPR-Cas therapies like Casgevy for SCD and β-thalassemia; analysis of in vivo vs ex vivo methods.	First CRISPR therapy (Casgevy) approved; promising safety and efficacy in SCD/TDT; highlighted delivery and off-target challenges.	[23]
Advances in CRISPR-Cas technology and its applications	Systematic review focused on molecular improvements in Cas9/Cas12 systems, plus therapeutic uses.	Enhanced specificity, base/prime editors progressed; therapeutic potential confirmed in preclinical and early clinical stages.	[24]
Past, present, and future of CRISPR genome editing technologies	Comprehensive review across basic biology, delivery systems, clinical hurdles.	Highlighted prime editing, base editing, and delivery limitations; promising for precision medicine.	[25]
A Comprehensive Review of mRNA Vaccines	Meta-analysis of mRNA vaccine platforms, particle design, stability, clinical success.	LNP breakthroughs, stability tweaks, freeze-drying techniques; highlighted broad pipeline.	[26]
Decoding trends in mRNA vaccine research	Bibliometric analysis between 2020–2024 with keyword mapping and clinical statuses	Rapid growth post-2020; dominance of COVID-19 applications; now shifting to cancer, flu, personalized vaccines.	[27]
Revolutionizing immunization: a comprehensive review of mRNA vaccine technology and applications	Narrative review; structural and delivery mechanism deep dive	Summarized LNP design, cap/poly-A modifications; discussed cold chain limitations.	[28]
COVID-19 mRNA vaccines: Platforms and current developments	Review of four mRNA platform types and vaccine candidates for viral diseases	Nucleoside-modified RNA dominated; noted circular mRNA innovations; successful clinical progress.	[29]
Progress and prospects of mRNA-based drugs	Analysis of preclinical and early clinical mRNA therapeutics for immune and non-immune uses	Highlighted dual immunogenicity challenge; pipeline expanding in cancer and protein-replacement therapies.	[30]
Mapping global public perspectives on mRNA vaccines	Social media sentiment analysis (Twitter) Jun 2022–May 2023	Found 69.5% negative sentiment; variation across regions; emphasized communication strategies.	[31]
Advancing CRISPR genome editing into clinical trials	Review of clinical uses in cancer, HIV, SCD; challenges of delivery, safety, ethics	SCD therapies approved (Casgevy); trials in oncology; noted off-target and regulatory limitations.	[32]
CRISPR-Based Therapies: Revolutionizing Drug Development	Examined CRISPR in therapeutic target validation and gene therapy workflows	Demonstrated use in diverse diseases; emphasized precise screening tools and therapy design.	[33]
CRISPR/Cas and AI to improve precision medicine	Review of AI-CRISPR integration for gene target discovery and editing	AI pipelines enable optimal gRNA designs; predictive models reduce off-target events.	[34]
Nanorobotics in Medicine: Advances, Challenges, Prospects	Systematic PRISMA review of PubMed/IEEE databases on nanorobotic diagnostics	414 studies; field growing in drug delivery, microsurgery; challenges in biocompatibility noted.	[35]
Self-amplifying RNA vaccine platforms	Review of self-amplifying RNA (saRNA) trials for COVID boosters	Phase 3 saRNA Omicron boosters effective; approval granted; noted delivery needs.	[36]
mRNA Folding Algorithms for Structure and Codon Optimization	Computational survey of folding algorithms to enhance mRNA stability	Identified key tools improving mRNA half-life and protein yield; applied to vaccines and therapeutics.	[37]
Gene Therapy Advances: FDA Approvals 2023–2024	Case review of FDA-approved gene therapies (e.g., BELOCEP, Elevidys, Casgevy)	High efficacy in rare diseases; vectors optimized; attention needed on long-term safety.	[38]

Beyond molecular therapeutics, nanorobotics emerged as a transformative force in diagnostics and drug delivery. A PRISMA-based review covering over 400 studies confirmed the growing role of nanorobots in microsurgery, site-specific drug release, and real-time biosensing. These precision tools were increasingly integrated with AI-based navigational systems to enable autonomous decision-making within the human body, identifying diseased tissues and releasing drugs with micrometer-level accuracy. Although challenges such as biocompatibility and mass production remained, early successes suggested that these tools could revolutionize minimally invasive treatments [35].

The cumulative impact of these innovations was evident in the rising number of FDA-approved gene therapies. Between 2023 and 2024, therapies such as BELOCEP, Elevidys, and Casgevy were approved, showcasing high efficacy in treating rare and inherited conditions. While delivery vectors and editing tools improved, researchers cautioned that long-term safety data and post-market surveillance remained crucial for sustained success [38]. Moving forward, the synergistic application of AI-augmented CRISPR systems, optimized delivery technologies, and mRNA-based therapies represented a convergence that could redefine the future of medicine, advancing from generalized treatments to hyper-personalized, gene-level interventions.

3.3. Biotechnology in environmental science.

Biotechnology played a crucial and rapidly evolving role in addressing environmental challenges, especially in the management and remediation of microplastic pollution and other persistent contaminants. Across multiple studies, there was a clear consensus on the rising potential of microbial, algal, and fungal systems to biologically degrade harmful pollutants in ecosystems. A systematic review on biotechnological methods to remove microplastics emphasized the identification of specific enzymes, such as hydrolases derived from *Bacillus* and *Pseudomonas*, which effectively broke down plastic polymers, while also recommending advanced gene-editing techniques and bioinformatics for improved efficiency and specificity in environmental applications [39]. These bacterial enzymes offered rapid degradation under controlled lab conditions, yet their activity was often limited by environmental variables such as pH, temperature, and substrate availability in field settings—posing challenges for real-world deployment and scalability.

Complementing this, another systematic review demonstrated that various enzyme-mediated pathways showed real potential in degrading microplastics, though it highlighted the need for field-based validation to assess real-world effectiveness [40]. While bacterial systems offered speed and high specificity, their application in diverse natural environments was constrained by low survival rates, potential ecological disruptions, and the cost-intensive nature of cultivating large bacterial populations at scale. Compared to fungi and algae, bacteria often required more controlled environmental parameters, which increased operational costs in open systems or large-scale remediation projects.

Microalgae emerged as vital agents in environmental biotechnology, especially for the bioremediation of pollutants such as dyes, heavy metals, and pharmaceutical waste. Meta-analyses and bibliometric studies confirmed that microalgae exhibited high uptake efficiency, particularly when combined with nanotechnology, resulting in hybrid systems that enhanced pollutant removal capacity [41]. Marine microalgae offered dual benefits by not only removing pollutants through biosorption and biomass accumulation but also converting waste into valuable by-products such as biofuels and bioplastics. Unlike bacterial systems, algal approaches provided a more sustainable and economically integrated model, as the biomass itself became a source of value-added products. However, despite these multifaceted benefits, algae-based systems suffered from harvesting inefficiencies, photobioreactor costs, and variable growth rates, especially under fluctuating outdoor conditions. These scalability challenges made it difficult to compete with more conventional remediation technologies without further innovations in system engineering.

These processes were further enhanced through genetic modification, increasing both environmental and economic returns [42]. A narrative review of algal wastewater systems echoed these benefits but also pointed out significant bottlenecks in economic feasibility and the need for improved harvesting technologies [43]. Compared to bacteria, algae required more spatial and light resources, which limited their application in densely populated or urban environments. Nevertheless, their ability to integrate into circular bioeconomy frameworks gave them a comparative edge in long-term sustainability.

Microalgae were also central to sustainable bioplastic production. Advances in microalgal bioplastics demonstrated that biofilm-based cultivation systems could increase bioplastic yields, although there remained a pressing need for improvements in system stability and scalability [44]. In comparison, fungal systems, especially filamentous fungi, showed promise in producing polyhydroxyalkanoates (PHAs) and other biodegradable materials, though their metabolic rates and enzymatic capacities for degrading complex pollutants tended to be slower than bacteria or algae. Reviews of third-generation biomass for bioplastics stressed the scalability of PHA production from microalgae using optimized reactor designs and metabolic engineering strategies, although downstream processing remained a significant hurdle [45]. High-energy input for extraction and purification continued to hinder economic feasibility, creating a gap between lab-scale success and industrial implementation. By contrast, fungal biomass often required less energy to process but yielded lower volumes and longer growth cycles, which could offset its cost benefits.

The environmental role of biofilms also extended to their interaction with microplastics; a systematic review highlighted that microbial biofilms altered the physicochemical properties of microplastics, facilitating their degradation and calling for integrated mitigation frameworks [46]. Here, fungi and bacteria often formed complex biofilms that could attach to microplastic surfaces, changing their hydrophobicity and making them more susceptible to enzymatic attack. While biofilm-based degradation offered promising synergy between microbial communities, it also presented regulatory and ecological uncertainties, particularly regarding the long-term fate of altered microplastics and biofilm-derived metabolites.

Comprehensive studies also reaffirmed the role of microbial consortia in degrading microplastics and other environmental wastes. One review examined the emerging threat of microplastics and presented microbial, algal, and fungal remediation techniques, recommending the use of genetically edited microbes supported by bioinformatics tools for enhanced degradation capabilities [47]. The use of engineered microbial consortia blend of species with complementary metabolic pathways, aimed to overcome the limitations of single-organism systems by offering greater resilience and versatility across environmental contexts. However, controlling interspecies interactions and maintaining balance in large-scale bioreactors remained a technical challenge with implications for operational stability and cost.

Another narrative review reinforced the ecological importance of bacteria, fungi, and plants in bioremediation, advocating for the development of engineered microbial consortia to enhance performance across various ecosystems [48]. Fungal systems, particularly white-rot fungi like *Phanerochaete chrysosporium*, showed unique abilities to degrade persistent organic pollutants via ligninolytic enzymes. Compared to bacteria and algae, fungi offered deeper substrate penetration and degradation of high-molecular-weight polymers, making them ideal for soil and sediment remediation. Yet, their slower growth rate and sensitivity to environmental stressors could delay remediation timelines and require more extensive field management.

Supporting this, a PRISMA-based synthesis identified *Bacillus*, *Pseudomonas*, and *Rhodococcus* as key bacterial taxa capable of degrading microplastics through specialized enzymatic pathways but acknowledged the challenges of scaling these solutions for broader environmental application [49]. These organisms remained central to microbial remediation strategies, but their mass cultivation, field deployment, and genetic containment continued to raise concerns in both ecological and regulatory domains. Finally, a systematic review of microplastic degradation processes provided an integrated overview of biological, physical, and chemical approaches, promoting enzyme- and biofilm-based solutions as key routes to inform effective policy and regulatory frameworks [49]. Integrating these approaches by combining biofilm-forming microbial consortia, AI-enhanced enzyme design, and adaptive delivery systems could enable scalable, cost-effective, and ecologically sound solutions. However, the current economic models indicated that without substantial investment in bioprocess optimization and infrastructure, many of these technologies would remain constrained to pilot-scale applications.

Table 3. Comparison of studies on biotechnology applications in environmental science.

Title of the Study	Methods	Findings	Environmental Context	Sources
Biotechnological approaches for microplastic degradation	Combined PRISMA reviews analyzing microbial (bacteria, algae, fungi) degradation, gene-editing, and bioinformatics tools	Identified key enzymes (e.g., hydrolases from *Bacillus*, *Pseudomonas*); stressed need for enzyme engineering and real-world validation	Freshwater, Soil, Marine	[39, 40]
Microalgae-based remediation of refractory pollutants	Bibliometric and meta-analysis on microalgal removal of dyes, metals, and pharmaceuticals; nanotech-enhanced systems included	High pollutant uptake; nanotechnology boosts efficacy; applicable to emerging contaminants	Industrial Wastewater, Freshwater	[41]
Marine microalgae for pollutant removal and biomass valorization	Review of marine algal biosorption and biomass-to-product pathways	Algae remove pollutants and generate biofuels/bioplastics; benefits enhanced through genetic engineering	Marine	[42]
Microalgae in wastewater treatment systems	Narrative review of algal-based removal of nutrients and metals	Proven removal efficiency; limited by economic viability and harvesting technology	Industrial Wastewater	[43]
Microalgal biofilms for sustainable bioplastics	Techno-economic review of biofilm-based cultivation and bioplastic yield optimization	Increased yield via biofilms; stability and scaling are key limitations	Industrial Wastewater	[44]
Third-generation biomass for PHA production from algae	Assessment of reactor designs and metabolic engineering strategies	Scalable production identified; downstream processing remains a barrier	Industrial Wastewater	[45]
Microbial biofilms and microplastic interactions	Systematic review of microbial colonization on microplastics	Biofilms alter MP properties; promote degradation; support integrated mitigation	Marine, Freshwater	[46]
Microbial and algal remediation of microplastics	Narrative review combining bacterial, fungal, and algal approaches with biotech interventions	Confirmed potential of gene-edited microbes; advocated bioinformatics-supported strategies	Freshwater, Soil, Marine	[47]
Microbial consortia in environmental waste bioremediation	Review of bacterial, fungal, and plant roles across ecosystems	Advocated use of engineered microbial consortia for ecosystem-specific remediation	Soil, Freshwater, Industrial Wastewater	[48]
System-wide review of microplastic degradation processes	PRISMA-based synthesis of physical, chemical, and biological methods	Developed comprehensive framework for enzymatic, biofilm-based, and policy-driven solutions	Freshwater, Marine, Soil	[49]

3.4 Biotechnological tools in agriculture, medicine, and environmental science.

As depicted in Table 3 and Figure 1, biotechnology has become a cornerstone in advancing agriculture, medicine, and environmental science. In agriculture, innovations such as GMOs and CRISPR-Cas9 gene editing have transformed food production, addressing global challenges in food security, climate resilience, and sustainability. GMOs involve the targeted modification of an organism's genetic material to confer desirable traits such as pest resistance, faster growth, and higher yields. This approach reduces reliance on chemical pesticides, lowering production costs and minimizing environmental toxicity. For instance, Bt corn, engineered with a gene from *Bacillus thuringiensis* exhibits natural insect resistance, significantly cutting pesticide use while boosting yields in regions such as North America and Southeast Asia [50]. These economic and ecological benefits underscore the growing role of GMOs in combating global hunger and promoting sustainable agriculture.

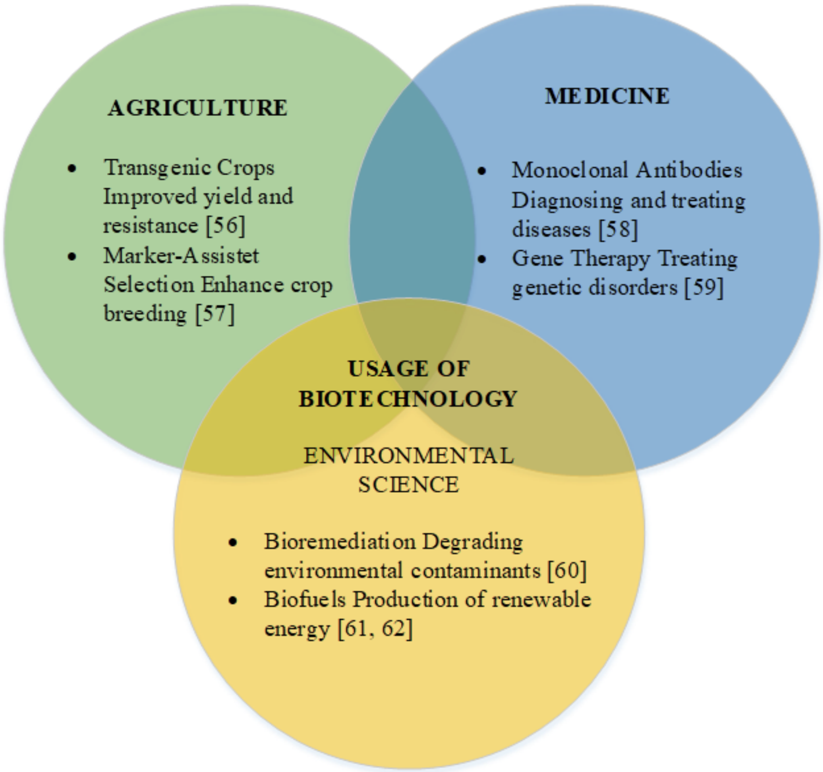

Figure 1. Biotechnology's contributions to agriculture, medicine, and environmental science.

CRISPR-Cas9 complements GMOs by enabling precise, efficient alterations to plant DNA. This tool is now widely applied to develop drought-tolerant, disease-resistant, and nutrient-enriched crops, addressing pressures from climate variability and resource scarcity [51]. Increasingly, CRISPR is paired with AI to enhance accuracy and impact. AI processes vast agricultural datasets including genomic sequences, soil health, weather patterns, and phenotypic traits, to identify optimal gene edits. By modeling plant–environment interactions, AI refines guide RNA selection and editing strategies, accelerating the development of crops suited to marginal lands, drought-prone climates, and nutrient-deficient soils. This AI–CRISPR synergy supports climate-smart, high-yield, and sustainable farming.

In medicine, biotechnology is reshaping healthcare through innovations that improve diagnosis, treatment, and therapeutic delivery. A foundational milestone is recombinant DNA technology, which enables the insertion of specific genes into microbial hosts to produce therapeutic proteins. This technique underpins the mass manufacture of insulin, vaccines, human growth hormone, and monoclonal antibodies revolutionizing treatment for diseases such as diabetes, hepatitis, and cancer [52]. Its precision and cost-effectiveness have also improved access to lifesaving medicines, particularly in low-income countries.

Another transformative area is stemming cell therapy, which harnesses undifferentiated cells capable of developing into specialized tissues. These therapies offer regenerative solutions for conditions once deemed incurable, including Parkinson's disease, spinal cord injuries, and cardiac degeneration [53]. Personalized stem cell treatments, tailored to a patient's cellular profile, reduce immune rejection and improve efficacy, representing a paradigm shift in modern medicine.

In environmental science, biotechnology provides sustainable, nature-based solutions to restore degraded ecosystems. Bioremediation, as shown in Table 3, employs bacteria, fungi, or genetically modified microbes to degrade hazardous pollutants such as petroleum hydrocarbons, pesticides, and heavy metals [54]. For example, *Pseudomonas* species are widely used to clean oil spills in marine environments. Similarly, phytoremediation uses plants such as sunflowers, Indian mustard, and willows to absorb and detoxify heavy metals like arsenic, lead, and cadmium from soil and water [55]. This cost-effective, low-impact approach rehabilitates contaminated lands, including mining sites and industrial zones, while enhancing biodiversity and ecosystem resilience.

Collectively, these advances in agriculture, medicine, and environmental science—illustrated in Figure 1 and summarized in Table 4 highlight biotechnology's transformative potential in addressing urgent global challenges. By integrating biological science with digital tools such as AI and emphasizing sustainability, biotechnology is shaping a resilient, healthy, and equitable future.

Table 4. Biotechnology's transformative potential in addressing urgent global challenges.

Field	Biotechnological Tool or Technique	Application	Impact	Sources
Agriculture	GMOs	Development of pest-resistant and high-yield crops	Improves food security and reduces pesticide use	[50]
	CRISPR-Cas9 Gene Editing	Precision breeding for drought-tolerant crops	Increases crop resilience to climate change	[51]
Medicine	Recombinant DNA Technology	Production of insulin, vaccines, and therapeutic proteins	Improves disease treatment and accessibility of medicine	[52]
	Stem Cell Therapy	Treatment of degenerative diseases and tissue regeneration	Revolutionizes regenerative medicine and personalized therapy	[53]
Environmental Science	Bioremediation using Microbes	Degradation of oil spills and toxic waste using bacteria	Reduces environmental pollutants cost-effectively	[54]
	Phytoremediation	Use of plants to remove heavy metals from contaminated soils	Promotes eco-friendly and sustainable soil restoration	[55]

Figure 1 presents a Venn diagram illustrating the diverse applications of biotechnology across three major sectors: agriculture, medicine, and environmental science. At their intersection lies the shared use of biotechnology, leveraging biological systems or living organisms to develop or modify products for specific purposes. In agriculture, biotechnology enables the creation of GMOs with enhanced yield, pest resistance, and drought tolerance [56, 57]. AI supports this sector by processing large datasets on soil composition, weather patterns, crop health (via satellite imagery), and genomic profiles. These analyses predict phenotypic traits, observable characteristics shaped by genetic and environmental factors, which guide CRISPR-Cas9 genome editing to achieve precise modifications, such as improved disease resistance or nutritional quality. In medicine, biotechnology drives innovations like gene therapy and precision drug development, both significantly advanced by CRISPR's targeted editing capabilities [58, 59]. In environmental science, it underpins bioremediation, biofuel production, and biodiversity conservation through genetically engineered organisms that degrade pollutants or generate sustainable energy [60–62]. This central role of biotechnology demonstrates how scientific innovation converges to address urgent challenges in food security, health care, and ecological sustainability.

3.5 Synthesis of the literature review.

The literature indicates that biotechnology has significantly advanced innovation in agriculture, medicine, and environmental science. While each sector benefits from unique applications, they share common tools and objectives particularly in enhancing human welfare and promoting sustainability. In agriculture, biotechnology supports the development of genetically modified (GM) crops that resist pests, diseases, and adverse climatic conditions. Techniques such as genetic engineering, tissue culture, and molecular markers improve crop yield and quality, reduce reliance on chemical inputs, and strengthen food security. Studies consistently show that when applied responsibly, biotechnology enhances productivity while reducing environmental impact.

In medicine, biotechnology has driven major breakthroughs in disease diagnosis, treatment, and prevention. Recombinant DNA technology, CRISPR gene editing, and monoclonal antibody production are instrumental in developing vaccines, treating genetic disorders, and enabling personalized medicine. Literature highlights the life-saving role of these innovations, especially during global health emergencies such as the COVID-19 pandemic.

In environmental science, biotechnology is harnessed to monitor, mitigate, and reverse ecological damage. Bioremediation and bioaugmentation employ engineered microorganisms to degrade pollutants in soil and water, while bioindicators detect ecosystem changes. These strategies illustrate biotechnology's role in maintaining ecological balance and reducing human impact on the planet.

A comparative analysis reveals that tools like genetic engineering, molecular diagnostics, and bioinformatics are widely applied across all three sectors. Although their specific uses vary, their shared purpose is to address critical challenges through scientific innovation. This cross-sector overlap highlights the increasing importance of interdisciplinary collaboration in tackling global issues such as food insecurity, health crises, and climate change.

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Author Contribution

The author is solely responsible for the entire development of this literature review. This includes the conceptualization of the study, the formulation of methods, and the application of inclusion criteria and PRISMA guidelines in screening and selecting relevant sources. The author also undertook the gathering of updated literature, sorting and organizing of the reviewed data, and the comprehensive analysis and synthesis of findings across the agriculture, medicine, and environmental science sectors. All write-ups, interpretations, and final revisions were likewise completed solely by the author.

Competing Interest

The author declares that there are no competing interests, financial, professional, or personal, that could have influenced the conduct, analysis, or interpretation of this literature review. This work was carried out solely for academic and scholarly purposes, with integrity and impartiality upheld throughout the research process.

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