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Green biotech: innovations driving a sustainable future

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Abstract
Green biotechnology has emerged as a transformative approach to addressing global sustainability challenges. By leveraging biological systems, this field offers innovative solutions for eco-friendly agriculture, sustainable industrial processes, and environmental preservation. From genetically engineered crops reducing pesticide dependence to bio-based plastics and microbial bioremediation technologies, green biotech bridges the gap between ecological responsibility and technological progress. This literature review explores recent advancements in green biotechnology, highlights successful applications, and discusses the challenges and ethical considerations shaping its future. By fostering global collaboration and integrating emerging technologies, green biotechnology has the potential to drive a sustainable and resilient future.

Keywords: *Green biotechnology, Sustainable innovation, Environmental biotechnology, Bio-based solutions, Eco-friendly technologies.*

Introduction

Green biotechnology, often referred to as environmenttal or sustainable biotechnology, encompasses the application of biological systems and organisms to develop products and processes that promote environmental sustainability (Ezeonu et al., 2012). This field integrates principles from molecular biology, genetics, and ecology to address challenges in agriculture, industry, and environmental management. By leveraging natural mechanisms, green biotechnology aims to create solutions that are both innovative and eco-friendly (Badiyal et al., 2024). In the context of modern biotechnology, sustainability has become a paramount concern. Traditional industrial and agricultural practices have often led to environmental degradation, including pollution, loss of biodiversity, and climate change. Green biotechnology offers alternative approaches that minimize ecological footprints (Saikanth et al., 2023). For instance, the development of biofuels from renewable biological sources presents a promising avenue to reduce reliance on fossil fuels and mitigate greenhouse gas emissions. Additionally, the use of bioremediation techniques employs microorganisms to clean up contaminated environments, showcasing the potential of biological solutions in environmental restoration (El-Araby, 2024). The global community faces a myriad of environmental challenges that underscore the importance of sustainable practices. Climate change, driven by increased greenhouse gas emissions, poses significant threats to ecosystems and human societies. Biodiversity loss, resulting from habitat destruction and pollution, disrupts ecological balance and reduces the resilience of natural systems. Moreover, the overuse of chemical fertilizers and pesticides in agriculture has led to soil degradation and water contamination (Wang et al., 2024). Green biotechnology addresses these issues by promoting practices such as the use of biofertilizers and biopesticides, which enhance soil health and reduce chemical runoff. By focusing on sustainable solutions, green biotechnology plays a crucial role in mitigating environmental challenges and promoting a harmonious relationship between human activities and the natural world (Sreethu et al., 2023).

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Methodology

This systematic review adhered to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, ensuring transparency and reproducibility in the selection and evaluation of studies. The methodology aimed to provide a comprehensive overview of advancements in green biotechnology, with a focus on eco-friendly innovations, sustainable solutions, and their applications across various sectors.

Search Strategy

A meticulous search strategy was employed to identify relevant literature. The following databases were utilized for the search: PubMed, Google Scholar, Scopus, and Web of Science. These databases were chosen due to their extensive coverage of scientific literature, particularly in the fields of biotechnology, environmental sciences, and sustainability. The search included a combination of specific keywords, such as "Green biotechnology", "Sustainable innovation", "Environmental biotechnology", "Bio-based solutions", and "Eco-friendly technologies". Boolean operators (AND, OR) were applied to refine the search results and ensure comprehensive retrieval of relevant articles. The search was conducted within a publication date range of January 2010 to December 2024 to capture recent advancements and emerging trends. Filters were applied to include only peer-reviewed articles published in English.

Inclusion and exclusion criteria

To ensure the relevance and quality of the included studies, specific inclusion and exclusion criteria were applied:

Inclusion Criteria:

1. Publications written in English.
2. Studies focusing specifically on green biotechnology and its applications.
3. Research articles reporting on sustainable innovations, bio-based solutions, or eco-friendly technolo--gies.

Exclusion Criteria:

4. Studies unrelated to green biotechnology or sustainbility.
5. Review articles without original data or case studies.
6. Publications with insufficient methodological details or non-peer-reviewed content.

Study Selection Process

The initial search yielded 142 articles across the selected databases. Duplicate records were identified and removed using bibliographic management software (e.g., EndNote), resulting in 91 unique articles. A two-step screening process was then conducted:

Title and Abstract Screening. Two independent reviewers assessed the titles and abstracts for relevance to the study objectives. Articles that did not meet the inclusion criteria were excluded at this stage.

Full-Text Review. The remaining 54 articles underwent a thorough review of their full texts to confirm alignment with the inclusion criteria. Discrepancies between reviewers were resolved through discussion or consultation with a third reviewer.

Quality Assessment

To evaluate the quality and validity of the selected studies, a risk of bias assessment was performed using the Cochrane Risk of Bias Tool. Each study was rated on criteria such as methodological rigor, clarity of objectives, and reliability of results. Only studies rated as low or moderate risk of bias were included in the final analysis.

Data Extraction and Synthesis

Data were extracted systematically from the selected studies using a standardized data extraction form. The extracted information included study objectives, methodologies, key findings, and implications for green biotechnology. Data were organized and synthesized thematically to identify common trends, innovations, and challenges in the field. A narrative synthesis approach was adopted to integrate findings across diverse studies, highlighting advancements, applications, and future perspectives in green biotechnology. Quantitative data, where available, were summarized using descriptive statistics to provide additional insights. To provide a transparent overview of the study selection process, a PRISMA flow diagram is included (Fig. 1), detailing the number of records identified, screened, and included in the review, along with reasons for exclusion at each stage.

Agricultural biotechnology

Agricultural biotechnology has significantly advanced sustainable farming practices, particularly through the development of genetically modified (GM) crops designed to reduce pesticide usage. By incorporating genes that confer resistance to specific pests, these crops diminish the need for chemical pesticides, thereby lessening environmental contamination and promoting ecological balance (Hamdan & Tan, 2024).

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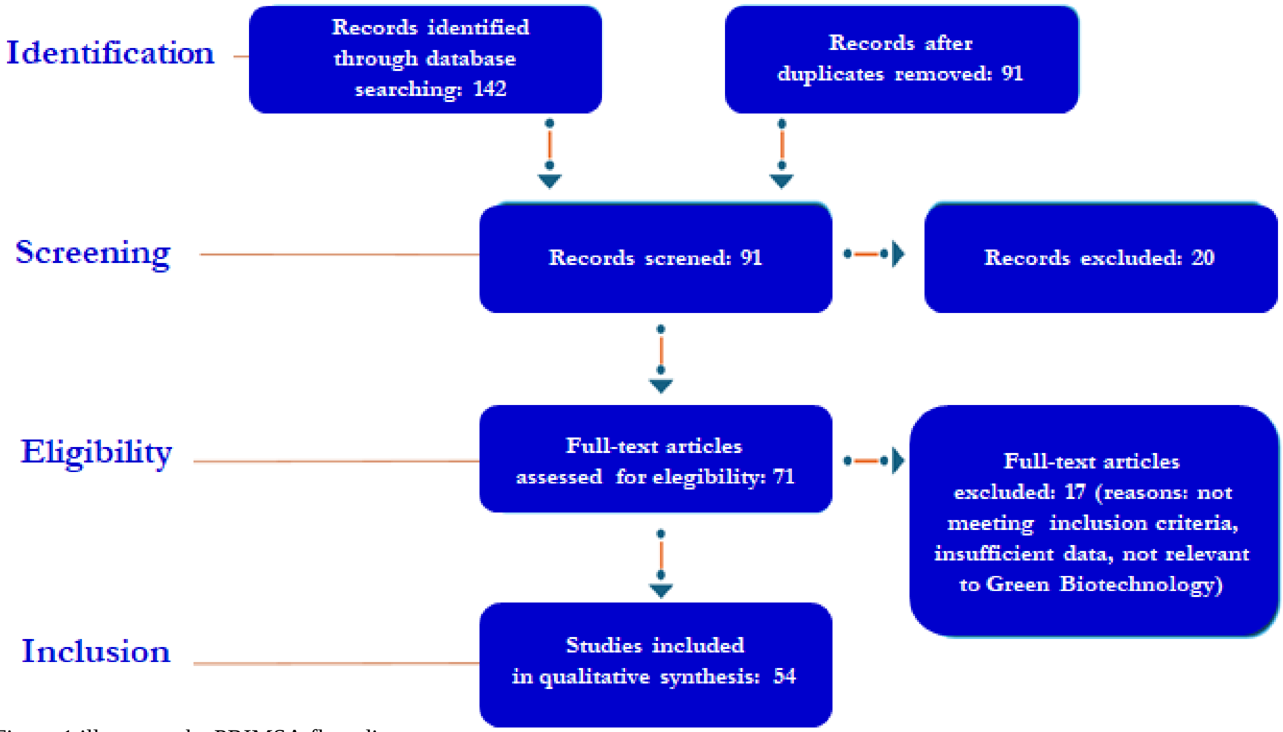

Figure 1 illustrates the PRIMSA flow diagram

For instance, Bt cotton, engineered to express *Bacillus thuringiensis* toxins, has effectively controlled bollworm infestations, leading to decreased pesticide applications and enhanced yields. A meta-analysis revealed that GM technology adoption reduced chemical pesticide use by 37%, increased crop yields by 22%, and increased farmer profits by 68% (Abbas, 2018). Complementing GM crops, biopesticides and biofertilizers have emerged as sustainable alternatives to conventional agrochemicals. Derived from natural organisms and substances, biopesticides offer targeted pest control with minimal non-target effects, reducing the ecological footprint of agriculture (Ayilara et al., 2023). Similarly, biofertilizers, which utilize beneficial microorganisms to enhance nutrient availability, improve soil fertility and structure, leading to increased crop productivity. These biological inputs not only support sustainable agriculture but also contribute to climate resilience by promoting healthier agro-ecosystems (Ammar et al., 2023). The development of drought-resistant and climate-adaptive crops is another critical focus of agricultural biotechnology. By identifying and introducing genes associated with stress tolerance, scientists have created crop varieties capable of maintaining productivity under adverse environmental conditions (Muhammad et al., 2023). For example, the U.S. Department of Agriculture has deemed a type of genetically modified wheat developed by Argentina's Bioceres Crop Solutions safe to grow in the United States. This HB4 wheat, modified for drought tolerance, must undergo additional steps including extensive field trials before commercialize-tion, a process that will take several years. This modification could be a significant advancement for farmers struggling with severe weather conditions (Miranda et al., 2022). These innovations are vital for ensuring food security in the face of climate change, enabling crops to with stand extreme weather events and resource limitations.

Industrial biotechnology

Industrial biotechnology has emerged as a pivotal field in developing sustainable solutions across various sectors, notably in the production of biodegradable plastics, the application of enzymes to minimize industrial waste and energy consumption, and the advancement of fermentation technologies for renewable biofuels (Nath, 2024). The shift towards bio-based manufacturing of biodegradable plastics addresses the environmental challenges posed by trade-tional plastics derived from fossil fuels. Innovative companies are creating bioplastic products from renewable sources like sugarcane, seaweed, and plant-based pigments. However, despite the promise of reduced carbon footprints and biodegradability, biopla-

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stics currently constitute only a small fraction of the market (Rosenboom et al., 2022). Challenges such as the need for industrial composting facilities and the presence of chemical additives complicate their environmental benefits. Regulatory frameworks in the U.S. and EU are being developed to encourage bioplastic production and ensure their sustainability, aiming to foster a transition to more eco-friendly materials (Moshood et al., 2022). Enzymes, as natural catalysts, play a crucial role in enhancing the efficiency of industrial processes, thereby reducing waste generation and energy consumption. For instance, in the production of bio-based chemicals, enzymes facilitate the conversion of raw materials into valuable products under milder conditions compared to traditional chemical processes (Jegannathan & Nielsen, 2012). This not only conserves energy but also minimizes the production of hazardous by-products. The Institute of Life Sciences highlights that enzymes are employed in various industries, including biofuels, where they assist in breaking down biomass into fermentable sugars, subsequently converted into ethanol. This enzymatic approach optimizes production processes, making them more energy-efficient and environmentally friendly (Malode et al., 2020). Fermentation technologies have been instrumental in the development of renewable biofuels, offering sustainable alternatives to fossil fuels. By utilizing microorganisms to ferment organic materials, these technologies produce bioethanol and biodiesel, contributing to reduced greenhouse gas emissions (El-Araby, 2024). In the UK, a pioneering initiative in the Western Isles involves converting non-recyclable waste into green fuel using fast-acting bacteria. This £1.2 million project processes domestic and commercial waste into solid recovered fuel (SRF), which emits 95% less CO_2 equivalent than traditional fossil fuels (Khan et al., 2020). Such advancements not only provide renewable energy sources but also offer innovative solutions for waste management, aligning with broader environmental sustainability goals.

Environmental biotechnology

Environmental biotechnology harnesses the capabilities of microorganisms and biological systems to mitigate pollution, manage waste, and address climate change through carbon sequestration (Kuppan et al., 2024b). Microbial bioremediation employs microorganisms to degrade or transform pollutants, offering an eco-friendly solution for environmental cleanup. In the case of oil spills, specific bacteria can metabolize hydrocarbons, effectively reducing contamination levels (Tedesco et al., 2024). For instance, certain bacterial strains have been utilized to degrade petroleum hydrocarbons in marine environments, enhancing the natural attenuation processes. Similarly, heavy metal pollution poses significant environmental and health risks (C. Li et al., 2023). Microorganisms can remediate heavy metal contamination through various mechanisms, including biosorption, bioaccumulation, and transformation. These processes involve the binding and uptake of heavy metals by microbial cells, leading to their removal or detoxification from contaminated environments (Kondakindi et al., 2024). In wastewater treatment, engineered organisms play a pivotal role in breaking down organic pollutants and removing nutrients. The use of phototrophic biofilms, which consist of photosynthetic microorganisms, has been explored for nutrient removal in wastewater treatment systems (Razzak, 2024). These biofilms can sequester nutrients from wastewater and utilize them, along with carbon dioxide, to build biomass, thereby improving water quality. Carbon sequestration technologies are critical in mitigating climate change by capturing and storing atmospheric carbon dioxide. Innovative approaches involve the use of microorganisms to enhance carbon capture (Bose et al., 2024). For example, certain bacteria can facilitate the precipitation of carbonates, effectively sequestering carbon in stable mineral forms (Qian et al., 2021). Additionally, the concept of iron fertilization in oceans has been explored, where the addition of iron stimulates phytoplankton growth, leading to increased carbon dioxide uptake and sequestration in ocean sediments. However, such geoengineering approaches require careful consideration due to potential ecological impacts and uncertainties (Jiang et al., 2024).

Advances in biomaterials

Advancements in biomaterials are significantly contributing to the development of sustainable alternatives to traditional materials, particularly through the innovation of bioengineered fibers and composites. These materials are designed to reduce environmental impact while maintaining or enhancing performance across various applications (Mahmud et al., 2024). In the fashion industry, traditional dyeing processes are known for their substantial water consumption and environmental pollution. Innovations in biomaterials have led to the development of sustainable alternatives, such as the use of pigment-producing bacteria

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for fabric dyeing (Lara et al., 2022). This method significantly reduces water usage and eliminates the need for harmful chemicals, resulting in a lower carbon footprint. An example is the Exploring Jacket, which utilizes bacterial pigments to achieve vibrant colors sustainably (Díez et al., 2025). In the construction sector, traditional materials like cement contribute significantly to carbon emissions. The development of bioconcrete, a type of concrete that incorporates biological components, offers a more sustainable alternative (Javeed et al., 2024). Bioconcrete not only reduces emissions during production but also enhances durability, leading to longer-lasting structures. The Gathering Lamp is an example of a product made from bioconcrete, demonstrating the material's versatility and environmental benefits (Ahmed et al., 2021). The field of polymer nanofibers has also seen significant advancements, particularly in biomedical applications. Techniques such as electrospinning have been utilized to fabricate functional polymer nanofibers with applications ranging from tissue engineering to drug delivery systems (Raizaday & Chakma, 2024). These nanofibers can be engineered to possess specific properties, such as biocompatibility and controlled degradation rates, making them suitable for various medical applications (El-Seedi et al., 2023).

Synthetic biology for sustainability

Synthetic biology is at the forefront of developing sustainable solutions through the creation of custom-designed organisms for green manufacturing and the application of gene editing to optimize energy-efficient crops (Burgos-Morales et al., 2021). In green manufacturing, synthetic biology enables the design of microorganisms tailored to produce valuable compounds with reduced environmental impact. By reprogramming the genetic circuits of bacteria, yeast, or algae, these engineered organisms can efficiently synthesize biofuels, biodegradable plastics, pharmaceuticals, and other essential materials (Rafeeq et al., 2022). This approach not only diminishes reliance on fossil fuels but also minimizes waste generation and energy consumption. For instance, engineered yeast strains have been developed to produce artemisinic acid, a precursor to the antimalarial drug artemisinin, offering a more sustainable and scalable production method compared to traditional extraction from plants (Smith & Chekan, 2022). Gene editing technologies, particularly CRISPR-Cas systems, have revolutionized the development of energy-efficient crops. By precisely modifying specific genes, scientists can enhance traits such as photosynthetic efficiency, drought tolerance, and nutrient utilization (Chen et al., 2024). These improvements lead to higher crop yields with reduced input requirements, contributing to sustainable agriculture. For example, gene editing has been applied to increase the efficiency of photosynthesis in rice plants, resulting in improved growth and yield under suboptimal conditions (Croce et al., 2024). The integration of artificial intelligence (AI) with synthetic biology further accelerates these advancements. AI algorithms can analyze vast datasets to predict the outcomes of genetic modifications, streamline the design of synthetic pathways, and optimize metabolic processes in engineered organisms (Huo & Wang, 2024). This synergy enhances the precision and efficiency of developing custom-designed organisms and gene-edited crops, expediting the transition to sustainable biomanufacturing and agriculture.

Case studies: success stories in green biotech

Green biotechnology has witnessed numerous success stories where innovative startups and global projects have significantly advanced sustainability. These cases offer valuable insights into effective strategies and the impact of green biotech initiatives (Nasser et al., 2021). One notable example is Constructive Bio, a pioneering company led by CEO Ola Wlodek. The firm focuses on creating new chemical building blocks and sustainable microbial factories by rewriting organisms' DNA to program cells efficiently, thereby reducing chemical waste (Wlodek, n.d.). Collaborations with pharmaceutical companies have led to improved drug manufacturing processes, including the production of semaglutide and antibody-drug conjugates for cancer treatment. This approach not only enhances efficiency but also minimizes environmental impact, exemplifying the potential of green biotechnology in pharmaceuticals (The Lancet Regional Health-Europe, 2024). In the realm of sustainable agriculture, Swiss startups such as ecoRobotix, Vivent, and Agro-Sustain have made significant strides. These companies develop environmentally friendly technological solutions that combine innovation, economic growth, and environmental protection (House of Switzerland, n.d.). Their success underscores the importance of integrating green technology in agriculture to promote sustainability. Global projects have also demonstrated the efficacy of green biotechnology in promoting sustainability. For instance, the Novo Nordisk Foundation funded twelve diverse biotechnology projects

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aimed at contributing to the green transition within agricultural and food production and industry (Asin-Garcia et al., 2024). These initiatives focus on creating new knowledge to ensure sustainable practices, highlighting the role of collaborative efforts in advancing green biotechnology. These examples illustrate the transformative potential of green biotechnology across various sectors. Key lessons from these success stories include the importance of interdisciplinary collaboration, the integration of innovative technologies, and a commitment to environmental sustaina--bility. By learning from these initiatives, future projects can effectively harness green biotechnology to address global environmental challenges.

Challenges and ethical considerations

Agricultural biotechnology has significantly advanced sustainable farming practices through the development of genetically modified (GM) crops, biopesticides, biofertilizers, and climate-resilient plant varieties (Das et al., 2023). Genetically modified crops have been engineered to reduce reliance on chemical pesticides, thereby mitigating environmental impacts. For instance, Bt cotton, which expresses a bacterial toxin lethal to specific pests, has led to a decrease in pesticide applications and associated greenhouse gas emissions (Abbas, 2018). A comprehensive study analyzing data from 1996 to 2020 concluded that GM crop adoption resulted in a global reduction of pesticide use by 7.2%, equivalent to 775.4 million kilograms (Brookes and Barfoot, 2020). Biopesticides and biofertilizers offer sustainable alternatives to synthetic agrochemicals. Derived from natural organisms or their byproducts, biopesticides, such as *Bacillus thuringiensis* (Bt) formulations, target specific pests while minimizing harm to non-target species and ecosystems (Samada and Tambunan, 2020). Similarly, biofertilizers, including Rhizobium and mycorrhizal fungi, enhance nutrient availability and soil health, promoting plant growth without the adverse effects associated with chemical fertilizers (Kumar et al., 2021). Thee development of drought-resistant and climate-adaptive crops is crucial in addressing the challenges posed by climate change. Advancements in genetic engineering have enabled the creation of crop varieties capable of withstanding abiotic stresses such as drought, salinity, and extreme temperatures (Muhammad et al., 2023). For example, the introduction of drought-tolerant maize in sub-Saharan Africa has demonstrated improved yields under water-limited conditions, contributing to food security in vulnerable regions (Fisher et al., 2015).

Future perspectives and emerging trends

The landscape of sustainable biotechnology is poised for transformative advancements, driven by emerging innovations, policy frameworks, and the integration of cutting-edge technologies (Gamage et al., 2024). One notable development is the creation of new chemical building blocks and sustainable microbial factories, exemplified by companies like Constructive Bio. By reprogramming organisms' DNA, these entities aim to produce chemicals and materials more efficiently, reducing chemical waste and environmental impact (Kumar et al., 2022). Policy and global collaboration play pivotal roles in steering the trajectory of green biotechnology. The Biotechnology Innovation Organization (BIO) emphasizes the importance of policies that enable biotechnology to reach its full potential as climate-tech, highlighting the need for supportive regulatory frameworks to foster innovation (Seid and Andualem, 2021). Furthermore, the United Nations Development Programme advocates for open business models that create value through systematic collaboration with external partners, such as public universities and research institutions, to promote sustainable agricultural practices (Filho et al., 2024). The convergence of artificial intelligence (AI) with biotechnology is another emerging trend with significant implications for sustainability. AI-driven approaches are being utilized to optimize bioproduction processses, enhance the efficiency of research and development, and accelerate the discovery of sustainable solutions (Chakravarthi et al., 2024). This integration facilitates the development of innovative products and processes that contribute to environmental sustainability.

Conclusions

In conclusion, green biotechnology stands at the forefront of addressing global environmental challenges by offering sustainable and innovative solutions across diverse fields, including agriculture, industry, and environmental remediation. From genetically modified crops reducing pesticide reliance to bio-based manufacturing of biodegradable plastics and advanced biomaterials, these innovations highlight the transformative potential of biotechnology in fostering sustainability. The integration of synthetic biology, artificial intelligence, and collaborative global efforts further propels this field toward a future marked by efficiency, reduced ecological footprints, and resilien-

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ce to climate change. As the world increasingly priori-tizes eco-friendly practices, green biotechnology is poised to play a pivotal role in shaping a sustainable and equitable future for generations to come.

Declarations

Availability of data and material: Data sharing not applicable to this article as no data-sets were generated or analyzed during the current study.

Competing interests: The author declare that they have no competing interests.

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