JOURNAL PARAK
Plant and Agribusiness Research of Applied Knowledge

Biotechnological Innovations for Sustainable Crop Production: A Systematic Literature Review on Productivity, Efficiency, and Environmental Impact

Padil Wijaya[1*], Tri Putri Nur[2], Guruh Mayka Putra[3], Ria Anita Pertiwi[4], & Nabilah Amiros[5]
[1*]Universitas Lambung Mangkurat, Indonesia, [2]Universitas Sriwijaya, Indonesia, [3]Universitas Lambung Mangkurat, Indonesia, [4]Universitas Lambung Mangkurat, Indonesia, [5]Universitas Sriwijaya, Indonesia
*Co e-mail: padilwijaya1997@gmail.com[1]

Article Information
Received: April 28, 2026
Revised: May 25, 2026
Online: June 03, 2026

Keywords
Sustainable Agriculture, Crop Production Innovation, Agricultural Biotechnology, Genetic Engineering

ABSTRACT

Maintaining environmental sustainability has become a major challenge for modern agricultural systems, increasing the need for innovative approaches in crop production. In this context, biotechnological innovation has emerged as an important strategy to support sustainable agriculture. This study aims to review the role of biotechnology in improving productivity, resource efficiency, and environmental sustainability through a systematic literature review approach. The study analyzes 20 peer-reviewed international journal articles focusing on genetic engineering, plant tissue culture, biofertilizers, biopesticides, and integrated biotechnological approaches. The findings show that biotechnological innovations improve crop resistance to pests and diseases, enhance productivity, strengthen resource-use efficiency, and reduce dependence on chemical inputs, thereby supporting environmentally sustainable agricultural practices. In addition, biological-based inputs contribute significantly to soil health, ecosystem balance, and long-term agricultural sustainability. However, challenges such as high implementation costs, regulatory barriers, unequal technological access, and limited public acceptance continue to hinder broader adoption, particularly in developing agricultural systems. Therefore, stronger policy support, research investment, institutional collaboration, and farmer education programs are needed to promote sustainable biotechnology adoption in agriculture. Overall, integrated biotechnological innovations represent a promising pathway toward sustainable crop production systems that balance productivity improvement with environmental conservation and long-term agricultural resilience.

DOI: https://dx.doi.org/10.69855/parak
Available online at website: https://gpijournal.com/index.php/parak
PUBLISHED BY : GPress Indonesia

INTRODUCTION

The rapid growth of the global population and the increasing demand for food have created significant challenges for agricultural systems worldwide. Ensuring food security while maintaining environmental sustainability has become one of the most critical issues in modern agriculture (Lee et al., 2021). Conventional farming practices, which often depend heavily on chemical fertilizers, pesticides, and extensive land use, are increasingly considered unsustainable due to their negative effects on soil health, water quality, and biodiversity (Idier et al., 2024). These limitations highlight the urgent need for innovative approaches that can improve crop productivity while preserving environmental resources (Padhiary et al., 2025). In addition, increasing climate variability and resource limitations have intensified pressure on agricultural systems to adopt more efficient and environmentally sustainable production strategies.

In this context, biotechnological innovation has emerged as a key driver in transforming agricultural systems toward more sustainable practices. Agricultural biotechnology encompasses a range of techniques, including genetic engineering, plant tissue culture, and the development of biofertilizers, which aim to enhance crop performance and resilience. These innovations enable the development of crop varieties with improved resistance to pests, diseases, and environmental stress, thereby reducing reliance on chemical inputs (Padhiary et al., 2025). As a result, biotechnology is increasingly recognized as an effective approach to support sustainable crop production systems (Singh, 2024). However, the effectiveness of these innovations varies across agricultural contexts and depends heavily on institutional support, farmer capacity, technological accessibility, and environmental conditions (FAO, 2024).

This review adopts a sustainability-oriented perspective that emphasizes the balance between agricultural productivity, environmental conservation, and resource efficiency, while also considering agroecological transition principles (Wezel et al., 2020). Recent studies have demonstrated that biotechnological applications contribute significantly to improving agricultural productivity and resource efficiency. Genetic improvement techniques allow the development of high-yield and stress-tolerant crop varieties, which can adapt to changing environmental conditions (Sharma, 2023). In addition, plant tissue culture techniques support the rapid propagation of high-quality planting materials, ensuring consistency and efficiency in crop production. These approaches not only increase yield potential but also enhance production stability, particularly under challenging environmental conditions (Padhiary et al., 2025). Nevertheless, several studies have also reported that the long-term sustainability impacts of certain biotechnological interventions remain uncertain, particularly regarding ecological balance, biodiversity preservation, and socio-economic inequality among farming communities.

Furthermore, the use of environmentally friendly biotechnological inputs, such as biofertilizers and biopesticides, has gained increasing attention in sustainable agriculture. These inputs help improve soil fertility and promote beneficial microbial activity, reducing the need for synthetic chemicals (Singh, 2024). By minimizing environmental pollution and maintaining soil health, biotechnological innovations contribute to long-term agricultural sustainability. In addition, these approaches support more balanced ecosystem interactions, which are essential for sustainable crop production systems (Idier et al., 2024). Despite these advantages, the implementation of biotechnology-based agricultural systems may involve trade-offs related to production costs, technological dependency, and varying levels of farmer readiness, particularly in developing countries.

Despite the promising potential of biotechnological innovation, several challenges hinder its widespread adoption. High research and development costs, strict regulatory frameworks, and limited public acceptance, particularly regarding genetically modified crops, remain significant barriers (Lee et al., 2021). In addition, disparities in technological access and knowledge among farmers can limit the effective implementation of biotechnological solutions. Existing studies also tend to focus on specific biotechnological applications rather than providing a comprehensive understanding of their collective role in supporting sustainable crop production systems (Idier et al., 2024). As a result, current literature provides limited understanding of how different biotechnological innovations interact collectively to influence sustainability outcomes across crop production systems, particularly across diverse socio-economic contexts (Chrisendo et al., 2026). Moreover, there is limited discussion on socio-economic, institutional, and policy-related factors that influence the adoption of biotechnology in different agricultural contexts (Padhiary et al., 2025). This fragmentation of existing studies makes it difficult to develop integrated strategies for sustainable agricultural transformation. Therefore, a more critical and integrative review is needed to address these gaps.

Based on the identified research gaps, this study aims to systematically review the role of biotechnological innovation in supporting sustainable crop production systems. The main research question addressed in this review is: How do integrated biotechnological innovations influence productivity, resource efficiency, and environmental sustainability in crop production systems? The objectives of this study are to identify key biotechnological approaches, analyze their impacts on productivity and environmental sustainability, and evaluate the challenges associated with their implementation. The novelty of this study lies in its integrative analytical approach, which examines the interactions among multiple biotechnological innovations and their combined implications for productivity, efficiency, and environmental sustainability. By integrating technological, environmental, and socio-economic perspectives, this review is expected to provide broader insights for future research directions, agricultural policy development, and sustainable farming practices.

METHODS

This study adopts a qualitative research approach using a systematic literature review (SLR) to examine the role of biotechnological innovation in supporting sustainable crop production systems. This approach is intended to provide a comprehensive and structured synthesis of existing research findings related to agricultural biotechnology and its contribution to productivity and environmental sustainability. The review procedure followed the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework to ensure a transparent and systematic selection process.

The subjects of this study consist of scientific articles related to biotechnological applications in agriculture, including genetic engineering, plant tissue culture, biofertilizers, and other biological-based innovations that support crop improvement and sustainability. Data were collected from Scopus, Web of Science, ScienceDirect, and Google Scholar databases. The inclusion criteria include: (1) articles published between 2020 and 2025, (2) studies focusing on biotechnological innovation in crop production, and (3) research discussing productivity, resource efficiency, or sustainability aspects. Meanwhile, exclusion criteria include non-peer-reviewed publications, conference abstracts, duplicated articles, and studies that are not directly related to crop production systems. Only peer-reviewed articles with clear methodological descriptions and relevant findings were included in the final analysis to ensure the quality and reliability of the reviewed literature.

The research procedure follows four main stages: identification, screening, eligibility, and inclusion. In the identification stage, relevant articles were collected using keywords such as “agricultural biotechnology,” “biotechnological innovation,” “sustainable crop production,” “genetic engineering in agriculture,” and “biofertilizers.” The search process used Boolean operators to improve search accuracy and comprehensiveness, such as (“agricultural biotechnology” OR “biotechnological innovation”) AND (“sustainable crop production” OR “crop sustainability”) AND (“biofertilizers” OR “genetic engineering”). The screening process involved removing duplicate and irrelevant articles based on titles and abstracts. The eligibility stage included a full-text review to ensure that the selected studies met the predefined criteria and aligned with the research objectives. Finally, the selected articles were included for further analysis.

The initial search identified 135 articles from the selected databases. After removing duplicated and irrelevant studies through title and abstract screening, 48 articles remained for eligibility assessment. Following a full-text review, 20 articles were selected for the final analysis. The materials used in this study consist entirely of secondary data derived from scientific journal articles, review papers, and related publications. All data used in this study were obtained from publicly accessible secondary sources.

Data collection was carried out through a structured literature search using academic databases and search engines. The selected articles were then organized and documented to facilitate the analysis process. The collected data include information on types of biotechnological applications, implementation approaches, productivity outcomes, and sustainability impacts. Data analysis was conducted using a qualitative content analysis approach. The selected studies were categorized based on key themes, such as crop improvement, input reduction, environmental sustainability, and technological application. The analysis involved coding, classification, and thematic synthesis to identify patterns, relationships, and key findings across the literature. To improve the transparency and replicability of the review process, detailed inclusion criteria, database sources, search strategies, and analytical procedures were systematically documented. In addition, a summary table of article characteristics was developed to classify the selected studies based on author, publication year, biotechnology type, and principal findings. To ensure the validity and reliability of the results, this study applies a transparent and systematic review process, including structured data collection and consistent analytical procedures. This methodological approach allows future researchers to replicate the study using similar databases, keywords, inclusion criteria, and analytical frameworks.

RESULTS

1. The Role of Biotechnological Innovation in Enhancing Crop Productivity and Sustainability

Across the reviewed studies, biotechnological innovation consistently emerged as a major factor in enhancing crop productivity and environmental sustainability. Most of the selected studies emphasized that biotechnology-based approaches, including genetic engineering, molecular breeding, and plant tissue culture, contributed significantly to increasing crop resilience, improving yield potential, and reducing dependency on chemical inputs. These innovations enable crops to adapt more effectively to environmental challenges such as drought, salinity, and pest attacks, thereby supporting more stable agricultural production systems. Lee et al. (2021) and Padhiary et al. (2025) similarly reported that biotechnology reduces reliance on synthetic fertilizers and pesticides while simultaneously improving environmental performance and agricultural efficiency.

A common pattern identified across the reviewed literature is the strong relationship between biotechnology adoption and improved resource-use efficiency. Several studies consistently reported that genetically improved crop varieties require fewer external inputs due to enhanced nutrient uptake efficiency and higher tolerance to environmental stress conditions. This finding is particularly important in modern agricultural systems where increasing production costs and environmental concerns have intensified the need for sustainable farming practices. Singh (2024) found that biotechnology-based crop management contributed to lower agrochemical usage and more efficient nutrient utilization, thereby supporting environmentally sustainable agricultural production.

Several reviewed studies also highlighted the important contribution of plant tissue culture in improving crop productivity and production stability. The findings indicate that tissue culture techniques support the rapid propagation of uniform and disease-free planting materials, which contributes to higher production consistency and reduced crop losses. This approach was reported to be especially effective for crops that are difficult to propagate conventionally or are highly vulnerable to disease transmission. Sharma (2023) emphasized that tissue culture technology improves the availability of high-quality planting materials and enhances overall crop performance under diverse environmental conditions.

Another important finding identified across the reviewed studies relates to the role of biotechnology in improving water and nutrient efficiency. Most studies reported that drought-tolerant and nutrient-efficient crop varieties contributed to more sustainable resource management by reducing excessive fertilizer and water use. These innovations were considered particularly beneficial in regions experiencing climate variability and water scarcity. Idier et al. (2024) reported that biotechnology-based agricultural practices support environmentally friendly farming systems by reducing the ecological footprint associated with intensive agricultural production.

Despite the generally positive findings, several studies also identified important limitations and implementation challenges associated with biotechnological innovation. A recurring issue across the literature involves high research and development costs, strict regulatory frameworks, and limited technological accessibility among small-scale farmers, particularly in developing countries. In addition, public concerns regarding genetically modified organisms were frequently reported as barriers affecting technology acceptance and adoption. However, the effectiveness of biotechnological innovations was found to vary depending on environmental conditions, institutional support, technological accessibility, and farmer capacity.

Overall, the reviewed studies indicate that biotechnological innovations significantly contribute to productivity enhancement, resource efficiency, and environmental sustainability, although adoption barriers remain significant in developing agricultural systems.

2. The Contribution of Biofertilizers and Biopesticides to Sustainable Crop Production Systems

Across the reviewed literature, biofertilizers and biopesticides consistently emerged as important biotechnological inputs that support sustainable crop production systems by improving soil fertility, reducing chemical dependency, and enhancing environmental sustainability. Most reviewed studies reported that biological inputs contribute to more efficient nutrient utilization and environmentally friendly pest management practices, thereby supporting long-term agricultural sustainability. Singh (2024) and Idier et al. (2024) similarly emphasized that biofertilizers improve soil fertility while reducing environmental pollution associated with excessive synthetic fertilizer use.

Several reviewed studies found that biofertilizers enhance nutrient availability and nutrient uptake efficiency through increased microbial activity in the soil. A recurring finding across the literature is that improvements in soil microbial diversity not only support soil fertility but also indirectly contribute to greater crop resilience, production stability, and long-term productivity. The reviewed studies also indicated that biological fertilizers contribute to improved soil structure and ecological balance, which are essential components of sustainable agricultural systems. Across the reviewed literature, environmental sustainability and reduced chemical dependency emerged as the most consistently reported benefits of biofertilizer application.

Several reviewed studies identified biopesticides as a sustainable alternative to synthetic pesticides due to their lower ecological toxicity and reduced risk of pest resistance development. The findings suggest that biopesticides contribute to safer agricultural production by minimizing chemical residues in crops and reducing harmful effects on non-target organisms and surrounding ecosystems. Padhiary et al. (2025) reported that the integration of biopesticides within pest management systems improves environmental performance while maintaining effective pest control. In addition, many studies emphasized that biopesticides support integrated pest management strategies by combining biological, mechanical, and cultural control approaches.

Another common pattern identified across the reviewed studies is the synergistic relationship between biofertilizers and biopesticides in improving overall crop performance and sustainability. Several articles reported that the combined use of these biological inputs enhanced nutrient efficiency, strengthened crop resistance to biological stress, and reduced yield losses caused by pests and diseases. Lee et al. (2021) similarly highlighted that biologically based agricultural inputs contribute to healthier soil ecosystems, which play a critical role in maintaining long-term agricultural productivity and environmental resilience.

The reviewed studies also consistently reported environmental benefits associated with the application of biological inputs. Most studies emphasized that biofertilizers and biopesticides reduce greenhouse gas emissions, minimize soil and water contamination, and support biodiversity conservation due to their biodegradable and environmentally compatible characteristics. These findings indicate that biological inputs contribute substantially to environmentally sustainable farming systems and ecological preservation.

Despite the generally positive findings, several studies also reported important implementation challenges and inconsistencies related to the effectiveness of biological inputs. A recurring issue identified across the literature involves variable field performance under different climatic, soil, and environmental conditions, which may reduce farmer confidence in adopting these technologies on a large scale. In addition, limited farmer knowledge, inconsistent product quality, short shelf-life of certain biological products, and insufficient policy support were frequently reported as barriers affecting broader adoption, particularly in developing agricultural systems.

Overall, the reviewed studies indicate that biofertilizers and biopesticides contribute substantially to sustainable crop production by improving soil fertility, reducing chemical dependency, enhancing crop resilience, and supporting environmental conservation, although implementation challenges remain significant across different agricultural contexts.

3. Integration of Biotechnological Innovations for Sustainable Crop Production Systems

Across the reviewed studies, integrated biotechnological approaches were consistently identified as more effective than single-technology applications in improving productivity, resource efficiency, and environmental sustainability within crop production systems. Several studies reported that the integration of genetic engineering, plant tissue culture, biofertilizers, and biopesticides provided greater sustainability outcomes compared to isolated biotechnological applications. This integrated approach allows agricultural systems to address multiple production challenges simultaneously, including crop productivity, nutrient efficiency, pest management, and environmental conservation. Padhiary et al. (2025) and Lee et al. (2021) emphasized that integrated biotechnological systems reduce dependency on synthetic agricultural inputs while improving ecological stability and long-term production sustainability.

A recurring finding across the reviewed literature is that the integration of biotechnology-based crop varieties with biological inputs significantly improves resource-use efficiency. Reviewed studies consistently showed that combining nutrient-efficient and stress-tolerant crop varieties with biofertilizers improved nutrient uptake efficiency, reduced fertilizer dependency, and enhanced soil quality. At the same time, the integration of biopesticides was reported to strengthen environmentally friendly pest management practices while minimizing ecological risks associated with synthetic pesticide use. Several studies further indicated that integrated systems contributed to more stable production outcomes by reducing vulnerability to environmental stress and pest outbreaks.

The reviewed literature also suggests that integrated biotechnological systems contribute substantially to sustainable intensification strategies. Most studies emphasized that integrated approaches increase agricultural productivity without requiring expansion of agricultural land, thereby supporting more sustainable land-use practices. In addition, integrated systems were frequently associated with improved conservation of soil and water resources as well as reduced environmental degradation. Several reviewed studies highlighted that sustainability improvements were achieved not only through reduced chemical input use but also through synergistic interactions between crop resilience, soil health, microbial diversity, and ecosystem stability.

Another important pattern identified across the reviewed studies relates to the role of integrated biotechnological systems in strengthening agricultural resilience to climate variability and environmental stress. Several studies consistently reported that stress-tolerant crop varieties combined with biologically improved soil conditions enhanced the adaptive capacity of farming systems under drought, salinity, and extreme weather conditions. Sharma (2023) similarly emphasized that integrated agricultural systems improve production stability and support long-term sustainability under changing environmental conditions.

Despite the generally positive findings, several studies also identified important challenges associated with the implementation of integrated biotechnological systems. A recurring issue across the literature involves high implementation costs, technological complexity, limited infrastructure availability, and restricted access to advanced technologies among smallholder farmers. In addition, some studies noted that the effectiveness of integrated systems depends heavily on institutional support, infrastructure quality, technological accessibility, and farmer capacity. Public concerns regarding certain biotechnological applications and inconsistent regulatory frameworks were also frequently reported as barriers limiting large-scale adoption.

Several reviewed studies further highlighted institutional support, extension services, and policy frameworks as critical factors influencing the successful implementation of integrated biotechnological systems. The findings indicate that collaboration among researchers, policymakers, and agricultural stakeholders plays an important role in facilitating technology dissemination, farmer adaptation, and long-term sustainability outcomes.

Overall, the reviewed studies indicate that the integration of biotechnological innovations provides a comprehensive approach to sustainable crop production by simultaneously enhancing productivity, improving resource efficiency, strengthening climate resilience, and reducing environmental impacts, although economic, technical, and institutional barriers remain significant across different agricultural contexts.

DISCUSSION

The findings of this study demonstrate that biotechnological innovation has become an increasingly important component of sustainability-oriented agricultural transformation. The consistency of findings across the reviewed studies suggests that biotechnology contributes not only to improving crop productivity but also to strengthening agricultural resilience under environmental stress conditions. Genetic improvement, tissue culture, and biologically based agricultural inputs were consistently associated with enhanced crop performance, greater adaptability to climate variability, and reduced dependency on synthetic agricultural inputs. These findings indicate that sustainability in crop production is increasingly dependent on the integration of biological efficiency, ecological resilience, and technological adaptability within agricultural systems. This interpretation extends previous studies that primarily emphasized productivity enhancement without fully addressing the interconnected relationship between productivity, environmental sustainability, and long-term agricultural resilience (Lee et al., 2021; Singh, 2024).

Another important insight emerging from the reviewed literature relates to the ecological contribution of biological inputs, particularly biofertilizers and biopesticides, in supporting environmentally sustainable farming systems. The reviewed studies consistently suggest that improvements in soil microbial activity, nutrient cycling, and ecosystem balance contribute significantly to long-term soil fertility and agricultural sustainability. Rather than functioning solely as alternatives to synthetic inputs, biological inputs appear to play a broader ecological role by supporting biodiversity conservation and reducing environmental degradation. This finding reinforces the perspective that sustainable agriculture should not be understood merely as input reduction, but as the development of more ecologically balanced and biologically integrated production systems.

The findings also highlight the importance of systems thinking in sustainable agriculture through the integration of multiple biotechnological innovations. Across the reviewed studies, integrated approaches consistently demonstrated greater effectiveness than isolated applications in improving productivity, resource-use efficiency, and environmental sustainability. The reviewed literature suggests that integration enhances sustainability not only through reduced chemical dependency but also by creating synergistic interactions between crop resilience, soil health, microbial diversity, and ecosystem stability. This systems-based perspective represents a significant conceptual shift from conventional productivity-oriented agriculture toward integrated sustainability-oriented agricultural management. Padhiary et al. (2025) and Sharma (2023) similarly emphasized that integrated agricultural systems provide more adaptive and resilient production outcomes under changing environmental conditions.

Despite the substantial benefits identified across the reviewed studies, the findings also reveal important implementation dilemmas and structural challenges associated with biotechnological innovation. Although biotechnology offers significant sustainability advantages, concerns regarding technological dependency, unequal access to innovation, high implementation costs, and regulatory disparities remain unresolved. These challenges are particularly evident in developing countries, where smallholder farmers often face limited financial resources, inadequate infrastructure, and weak agricultural extension systems. The reviewed literature suggests that adoption barriers are more pronounced in developing agricultural regions due to disparities in technological accessibility, institutional support, and farmer capacity. This finding indicates that the effectiveness of biotechnology is influenced not only by technological performance but also by broader socio-economic and institutional conditions.

The study further emphasizes the critical role of institutional support and policy frameworks in facilitating sustainable biotechnology adoption. Several reviewed studies highlighted that government support, research investment, extension services, and stakeholder collaboration significantly influence the successful implementation of biotechnological innovations. In this context, sustainability transitions in agriculture require not only technological advancement but also supportive governance structures and inclusive innovation systems. The findings suggest that stronger collaboration among researchers, policymakers, private sectors, and farming communities is essential to ensure that biotechnological innovations can be implemented more equitably and effectively across different agricultural contexts.

This study also provides several important implications for future research. Future studies should prioritize long-term comparative evaluations examining the ecological, economic, and social performance of integrated biotechnological systems across different agroecological regions. In addition, further research is needed to explore socio-economic adoption models, farmer accessibility to biotechnology, and policy mechanisms that support smallholder participation in sustainable agricultural transformation. Comparative regional studies involving developing countries are particularly important to better understand contextual differences in technology adoption and implementation effectiveness.

Despite its contributions, this study has several limitations. The review was limited to peer-reviewed articles published between 2020 and 2025 and primarily relied on selected international databases, which may have excluded earlier studies or relevant non-English publications. In addition, differences in research methodologies and regional contexts among the reviewed studies may influence the generalizability of the findings. Nevertheless, the study provides a comprehensive synthesis of current evidence regarding the role of biotechnological innovation in supporting sustainable crop production systems.

CONCLUSIONS

The findings of this systematic review suggest that the future sustainability of crop production systems increasingly depends on the successful integration of biotechnological innovations with ecological resilience and institutional support systems. Integrated biotechnological approaches emerged as the most effective strategy for simultaneously improving productivity, strengthening resource-use efficiency, enhancing environmental sustainability, and increasing agricultural resilience under changing environmental conditions. The reviewed studies consistently demonstrated that genetic engineering, plant tissue culture, biofertilizers, and biopesticides contribute substantially to the development of more adaptive and environmentally sustainable agricultural systems.

This review contributes to the existing literature by providing an integrated analytical perspective on how multiple biotechnological innovations collectively influence sustainable crop production systems. The findings indicate that agricultural sustainability is increasingly determined not only by productivity enhancement but also by the capacity of agricultural systems to balance ecological stability, environmental conservation, and long-term resource efficiency. However, the implementation of biotechnology remains constrained by economic limitations, unequal technological accessibility, institutional disparities, and regulatory complexity, particularly in developing agricultural regions.

Future studies should prioritize long-term comparative evaluations of integrated biotechnological systems across diverse agroecological and socio-economic conditions to better understand their environmental, economic, and social implications. Further research is also needed to examine technology accessibility, farmer adoption capacity, policy effectiveness, and institutional readiness in supporting inclusive and sustainable agricultural transformation.

This review is limited to peer-reviewed studies published between 2020 and 2025 and may not fully capture earlier developments or non-English literature related to agricultural biotechnology. Nevertheless, the study provides a comprehensive synthesis of current evidence regarding the strategic role of biotechnological innovation in supporting sustainable crop production systems and offers important implications for future agricultural sustainability research, policy development, and implementation practices.

ACKNOWLEDGMENT

The author would like to express sincere appreciation to all researchers whose studies contributed to this literature review. Gratitude is also extended to colleagues and academic contributors who provided valuable support and insights during the completion of this study.

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