ADVANCING SUSTAINABLE AGRICULTURE IN VIETNAM THROUGH BIOTECHNOLOGY AND ARTIFICIAL INTELLIGENCE

Phan Thi Huyen*

Department of Biotechnology, Faculty of Chemical Engineering, Ho Chi Minh City University of Technology (HCMUT), VNU-HCM, Ho Chi Minh City, Vietnam

*Email: *huyencnshbk@hcmut.edu.vn*

Received: 2 May 2025; Revised: 19 May 2025; Accepted: 31 May 2025

ABSTRACT

Vietnamese agriculture is increasingly vulnerable to the impacts of climate change, which has led to more frequent and severe crop diseases, making it challenging for farmers to sustain productivity. In response, the heavy use of chemical fertilizers and pesticides has resulted in soil degradation, raised serious food safety, public health concerns, and environmental problems. Addressing these issues requires a shift toward more sustainable agricultural practices that can support both productivity and ecological resilience. This paper examines how Vietnam can move toward a more sustainable agricultural model by integrating biotechnology and artificial intelligence (AI). Biotechnology provides innovative solutions that reduce dependence on harmful chemicals while improving soil quality and crop health. When integrated with AI, it can enhance the development of biofertilizers, biopesticides, and high-yield, climate-resilient crop varieties with greater precision and efficiency. Drawing on global case studies, this research highlights how Vietnam can adopt these technologies to tackle its specific agricultural challenges. The adoption of biotechnology and AI-driven solutions has the potential to transform Vietnamese agriculture into a high-tech, environmentally friendly system that balances productivity with sustainability. However, realizing this transformation requires substantial investment in biotech research and infrastructure, the development of a skilled workforce, and the establishment of clear, comprehensive regulatory frameworks for innovations. By learning from international experiences and adapting them to local conditions, Vietnam can build a resilient and sustainable agricultural future that ensures both food security and environmental protection in the face of climate change.

Keywords: Agricultural biotechnology, artificial intelligence, biofertilizers, biopesticides, CRISPR/Cas9, sustainable agriculture.

1. INTRODUCTION

Agriculture is a fundamental sector in material production, utilizing land, crops, and livestock to provide food and raw materials for industry. It intertwines economic activities with natural reproduction processes. In Vietnam, agriculture remains the backbone of the economy, contributing 12% to GDP and supporting over 62% of the rural population [1]. Rooted in indigenous knowledge and traditional practices, such as crop rotation, composting, and use of synthetic inputs, Vietnamese agriculture is labor-intensive but environmentally vulnerable, leading to nutrient depletion, erosion, and pollution [2-3]. Climate change has exacerbated these issues, with unpredictable weather and extreme conditions increasing the risk of crop diseases

[4-7], threatening food security and productivity [8]. Erratic rainfall, rising temperatures, and more frequent natural disasters have made crops more susceptible to pests and diseases [9], leading to yield declines [8, 10, 11]. In response, farmers have increasingly relied on chemical fertilizers and pesticides, which has come at a high environmental cost [13]. Overuse of agrochemicals has degraded soil fertility, disrupted microbial communities, and reduced biodiversity, especially in the Mekong Delta. Intensive rice farming, most notably triple-cropping systems, has led to an 85% loss of organic matter, a 30% drop in available nitrogen, and a 56% decline in phosphorus, severely impairing soil health and structure [12]. Disruption of soil microbial balance and a decline in beneficial insects have worsened pest resistance, particularly in species like the brown planthopper, prompting further pesticide use and ecological imbalance [12-13]. In addition, chemical residues on agricultural products raise serious concerns about food safety, posing potential health risks to consumers and creating challenges for exports due to strict international standards. In 2024, the European Union issued 114 warnings over excessive pesticide residues in Vietnamese products such as dragon fruit, chili, okra, and durian [14]. These interconnected challenges highlight the urgent need to shift toward more sustainable farming practices, methods that safeguard the environment, enhance farmers' livelihoods, and strengthen long-term resilience in the face of growing climate change threats.

Sustainable agriculture, as defined by Das et al. (2023), integrates plant and animal systems to meet food needs while preserving natural ecosystems [15]. It requires balancing economic, environmental, and social goals. However, transitioning from traditional to sustainable agriculture is a complex process, particularly in the face of abiotic stresses like soil degradation, nutrient deficiencies, and water depletion, as well as biotic stresses such as pests and diseases. Biotechnology involves applying biological technology, primarily through transferring specific traits via genetic material between plants or organisms, to enhance crop yields and improve tolerance to various stresses. Artificial Intelligence (AI) refers to technologies that enable machines and computers to replicate human intelligence, using algorithms, statistical models, and machine learning to mimic human functions such as learning, reasoning, and self-improvement [16]. This paper explores how biotechnology accelerated with AI can serve as powerful tools in addressing these agricultural challenges in Vietnam to promote sustainable agriculture.

2. BIOTECHNOLOGY IN SUSTAINABLE AGRICULTURE

Sustainable agriculture aims to nurture and maintain conditions that enable people and nature to live together productively, supporting present and future generations. Biotechnology in sustainable agriculture is the application of technology in biology to exploit biological processes and scientific advances to make agriculture more efficient, environmentally friendly and sustainable. It includes the use of tools such as genetic engineering and microbial applications to improve crop yields, reduce chemical use, and conserve natural resources. Genetic engineering is the process of directly altering the DNA of organisms to create new traits or enhance existing ones. It specifically refers to the use of biotechnology to manipulate an organism's genetic material for improved performance; Microbial applications involve the use of microorganisms such as bacteria, algae, fungi and plant residues in targeted ways. To promote sustainability in agriculture, beneficial microbes are used as biofertilizers to enhance soil health and nutrient availability, reducing the need for chemical fertilizers, and as biopesticides to offer environmentally friendly alternatives to chemical controls by targeting pests and diseases without harming beneficial organisms or the ecosystem. These tools enable the development of crops with higher yields, enhanced nutritional content, improved disease resistance, and better adaptation to environmental stresses.

2.1. Advanced genetic engineering

Due to the serious impacts of climate change on human health, food security, and the environment, crop plants have been extensively engineered to adapt to evolving conditions. A range of approaches, including crossbreeding, mutational breeding, polyploidy induction, protoplast fusion, transgenesis, and genome editing, have been employed [18]. Among these, genetically modified (GM) and CRISPR-based techniques have emerged as the most precise and efficient tools for modern crop breeding.

2.1.1. Genetically modified crops

GM crops are developed by inserting, deleting, or modifying genes to confer traits that do not naturally occur in the target species. Introduced in the 1990s, GM technology typically uses *Agrobacterium tumefaciens*, a bacterium that transfers genetic material via a tumor-inducing (Ti) plasmid into the plant genome [17]. This interspecies gene transfer enables precise trait enhancement, including increased yields, pest resistance, and nutritional improvements. Commercial GM crops, such as maize (*Zea mays*), soybean (*Glycine max*), and cotton (*Gossypium hirsutum*), have been widely adopted since 1994. By 2014, over 90% of these crops grown in the United States were GM varieties [17]. Despite widespread benefits, including reduced pesticide usage and improved adaptability to environmental changes [17], GM technology has raised concerns regarding potential risks to human health, ecosystems, and regulatory challenges [18]. Nonetheless, more than 30 GM crop varieties have been developed, including maize, soybeans, canola, rice, and potatoes, with traits tailored for agricultural improvement [17]. The yield of GM maize grown in Vietnam averages 8.7 tons/ha/crop, while that of traditional maize averages only 6.7 tons/ha/crop [19]. Other advantages of GM maize compared to conventional maize grown in Vietnam are presented in Table 1.

Table 1. Advantages of GM maize over conventional maize grown in Vietnam

Metric	Advantage	Source
Yield increase (%)	30.40%	[20]
Production cost reduction (USD/ha)	\$26.47 - \$31.30	[20]
Profit increase (USD/ha)	\$196 - \$330	[21]
Return on investment	\$6.84 - \$12.55 per \$1 invested	[20]
Insecticide use reduction	-78%	[20]
Environmental impact of the insecticide use	-77%	[20]
Herbicide use reduction	-26%	[20]
Environmental impact of the herbicide use	-36%	[20]

2.1.2. CRISPR-edited crops

CRISPR/Cas systems represent a transformative technology in precision plant breeding. As one of four key sequence-specific nucleases (SSNs), alongside meganucleases, zinc-finger nucleases (ZFNs), and transcription activator-like effector nucleases (TALENs), CRISPR/Cas stands out for its simplicity, cost-effectiveness, and flexibility [22-27]. The CRISPR (Clustered Regularly Interspaced Short Palindromic Repeats) technology is based on a natural defense mechanism bacteria use to protect themselves from viral infections. When a bacterium detects viral DNA, it generates two short RNA molecules, one of which matches the sequence of the invading virus. These RNAs form a complex with a protein called Cas9, a nuclease. When the matching sequence, called a guide RNA, finds its target in the viral genome, the Cas9 cuts the target DNA, disabling the virus. The system can be engineered to cut not only viral DNA but also any DNA sequence at a precisely chosen site by modifying the guide RNA to match the target. Once inside the nucleus, the resulting complex locks onto a short sequence known as the PAM, a protospacer adjacent motif, which is a 2–6-base pair DNA sequence immediately following the DNA sequence targeted by the Cas9 nuclease in the bacterial adaptive immune system [28]. The PAM is a component of the invading virus or plasmid, but is not found in the bacterial host genome and hence is not a component of the bacterial CRISPR locus. Cas9 will not successfully bind to or cleave the target DNA sequence if it is not followed by the PAM sequence. After Cas9 binds, the Cas9 will unzip the DNA and match it to its target RNA. If the match is complete, the Cas9 will use its two molecular scissors to cut the DNA. When this happens, the cell attempts to repair this break, but the repair process is error prone, often leading to mutations that can deactivate the gene, allowing researchers to study its function. These mutations are random but can be engineered to be more precise by replacing the mutant gene with a healthy copy. This can be done by adding another piece of DNA that carries the desired sequence. Once the CRISPR has made a cut, this DNA template can pair up with the cut ends, recombining and replacing the original sequence with the new version. Unlike GM technology, CRISPR can be used to target many genes at once. While GM crops have their genome added with external genes, CRISPR/Cas9 ones have their genome precisely edited at desired locations. In the world, potatoes with StDMR6-1 gene using CRISPR/Cas9 exhibited increased resistance to late blight disease and improved tolerance to drought and salinity, all without compromising yield or tuber quality [29-31]. Similarly, CRISPR/Cas9 has been used to engineer various crop varieties that are more resilient to abiotic and biotic stresses, while also improving their nutritional value, yield, etc. [27, 32-36]. The CRISPR-Cas system has also been applied to edit the genomes of insects for pest management purposes [31, 37]. This technology has revolutionized plant research, which enables precise crop breeding and offers new opportunities for engineering disease resistance traits for agricultural improvement [38, 39]. In Vietnam, significant progress has recently been made in applying this technology to successfully develop and test CRISPR-edited crop varieties with enhanced traits (Table 2).

Table 2. CRISPR-edited crop varieties developed in Vietnam

Plant	Enhanced trait	Institution	Source
Rice	Resistant to heavy metal accumulation and bacterial leaf blight	Agricultural Genetics Institute (Vietnam Academy of Agricultural Sciences)	[40]
Soybean	Reduction in indigestible sugar content and resistant to powdery mildew	Institute of Biotechnology (Vietnam Academy of Science and Technology)	[41]
Tomato	Increased sugar and amino acid content	Institute of Biotechnology (Vietnam Academy of Science and Technology)	[41]

2.2. Microbial applications

Microbial biotechnology offers sustainable alternatives to chemical inputs in agriculture. Beneficial microbes can improve plant health, reduce environmental damage, and support productivity. Two of the most impactful applications are biofertilizers and biopesticides.

2.2.1. Biofertilizers

Soil plays a vital role in agriculture as it acts as the foundational medium for plant growth, supplying water and essential nutrients needed for crop development. Maintaining healthy soil is critical not only for achieving high agricultural productivity but also for ensuring clean air and water and sustaining biodiversity within ecosystems. To support this, it is essential to improve soil fertility and structure, supply nutrients sustainably to enhance nutrient uptake and root development, and foster an environment that supports beneficial microorganisms. Despite these needs, current soil management practices rely heavily on inorganic, chemical-based fertilizers. These fertilizers, typically composed of synthetic nitrogen (N), phosphorus (P), and potassium (K), are designed to increase plant growth and yield. Although they have greatly contributed to agricultural advancement, their overuse or misapplication can harm both environmental and human health. Potential negative impacts include the decline of soil fertility, contamination of soil and water resources, destruction of beneficial microbial communities, and an increase in pest and disease outbreaks [41-45]. Excessive use of chemical fertilizers poses significant risks to human health, particularly through nitrate contamination and exposure to toxic chemical compounds. Such exposure has been associated with serious health conditions, including neural tube defects, solid organ tumors, blood-related cancers, and diabetes [46, 47]. Over time, Vietnam has increasingly used chemical fertilizers in agriculture (Fig. 1). In 2021, Vietnam ranked second in Southeast Asia in chemical fertilizer use, which accounted for 461.7 kg/ha, just after Malaysia (Fig. 2). Worse still, certain regions within the country exhibit even higher usage. For instance, the South East region averages 1,325 kg/ha, and the Central Highlands average 1,150 kg/ha, and an amount of about 40 to 60% of applied fertilizers in Vietnam are lost due to inefficiencies, leading to environmental pollution and greenhouse gas emissions [48].

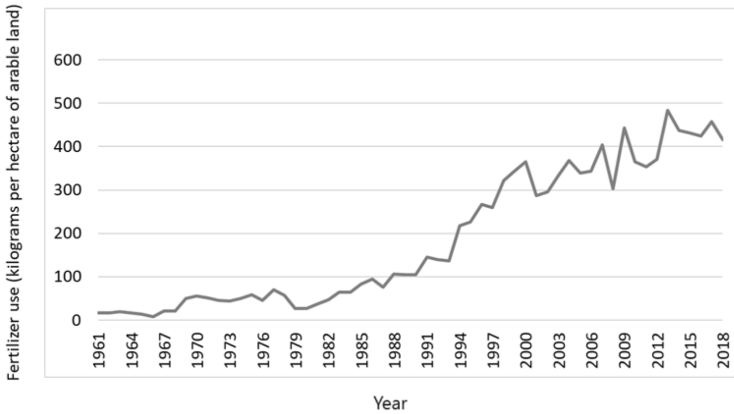

Figure 1. Fertilizer consumption in Vietnam over time [49].

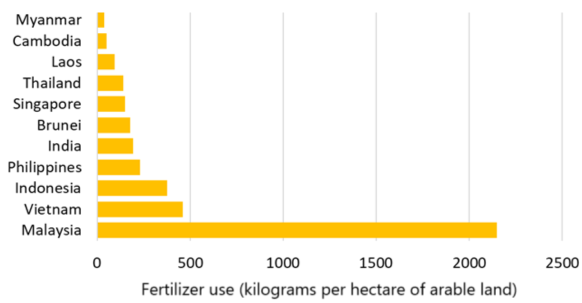

Figure 2. Fertilizers usage by South East Asian countries in 2021. Fertilizer products cover nitrogenous, potash, and phosphate fertilizers (including ground rock phosphate). Traditional nutrients (animal and plant manures) were not included [50].

Biofertilizers play a vital role in advancing sustainable agriculture by enhancing soil fertility, improving plant stress tolerance, and boosting crop productivity [51]. They contain beneficial microorganisms such as plant growth-promoting rhizobacteria (PGPR), arbuscular mycorrhizal fungi (AMF), and certain algae and fungi, which help maintain a nutrient-rich soil environment. These microorganisms contribute through processes like nitrogen fixation, solubilization or mineralization of phosphate, zinc, and potassium, secretion of plant growth regulators, antibiotic production, and the biodegradation of organic matter in soil. When applied to seeds or soil, biofertilizers multiply and actively participate in nutrient cycling, leading to improved crop yields. PGPR, in particular, enhance phosphorus availability, fix atmospheric nitrogen, produce siderophores that help plants access iron, and synthesize plant hormones such as gibberellins, cytokinins, and auxins. They also generate 1-amino cyclopropane-1-carboxylate deaminase, an enzyme that reduces ethylene levels in plants, thereby alleviating environmental stress. Together with AMF, PGPR can increase tolerance to drought and salinity, mitigate the effects of unfavorable soil pH, and assist in heavy metal removal. These plant-microbe interactions have been shown to improve seed germination, root development, leaf area, chlorophyll content, nutrient uptake, protein synthesis, shoot and root biomass, stress tolerance, biocontrol activity, and even delay leaf senescence [41, 44, 52-59]. BioGro is a plant growth-promoting biofertilizer developed in Vietnam, comprising nitrogen fixing and phosphorus solubilizing microorganisms, enhancing rice yields and reducing the need for chemical fertilizers [60].

Recent advancements in omics-based technologies and microbiome engineering have enabled the design of synthetic microbial communities (SynComs) that integrate multiple beneficial traits for studying microbe-plant interactions. Genomic data enables the reconstruction of microbial communities that naturally associate with plants under stress conditions. If not already available, these microbial consortia can be cultured and isolated from the environments where they interact with plants. They can then be inoculated onto plants in stress conditions for identifying stress-responsive genes [61, 62]. The stress-responsive genes can then be used to generate targeted mutants using CRISPR/Cas9 technology. Also, host-mediated microbiome engineering [63] leverages cutting-edge omics technologies to reintroduce genes responsible for synthesizing beneficial compounds, thereby enhancing plant-microbe interactions and enabling plants to naturally produce their own biofertilizers. These approaches not only increase nutrient availability within the rhizosphere – reducing dependence on chemical fertilizers and offering environmental benefits – but also strengthen the rhizosphere microbiome. This, in turn, improves plant health and resilience to both biotic and abiotic stresses.

2.2.2. Biopesticides

Pesticides are chemical agents used to manage pests and protect crops from diseases. They can be categorized by their target organisms: fungicides suppress fungal growth, herbicides (or weedicides) eliminate unwanted vegetation, nematicides combat parasitic worms, insecticides address insect pests such as aphids and caterpillars, rodenticides are used to control rodents like mice and rats, and bactericides target bacterial plant pathogens. Additionally, pesticides can be grouped based on their chemical structures, physical properties, and mechanisms of action. Among the earliest synthetic pesticides were organochlorines, primarily used for insect control. Other classes include carbamates and organophosphates, both of which interfere with pest nervous systems but can also impact non-target species. Pyrethroids, synthetic analogs of natural insecticidal compounds, and neonicotinoids, which are chemically similar to nicotine, also act on the nervous systems of insect pests [64-66].

Pesticides are very important in agriculture, because farmers use them to increase crop yields

[67]. While pesticides are crucial for safeguarding crops against various diseases and pests, their use must be carefully regulated and limited to recommended dosages. Excessive application can lead to severe health effects such as poisoning, paralysis, and even death. Prolonged exposure has also been linked to chronic health conditions including cancer, cardiovascular disease, respiratory problems, and neurological impairments [68]. Beyond human health, pesticide residues can contaminate the environment after application, negatively impacting non-target organisms such as beneficial insects, plants, animals, aquatic species, and birds [65]. In Vietnam, South Central Coast area uses up to 9.5 kg of pesticides per hectare (Fig. 3).

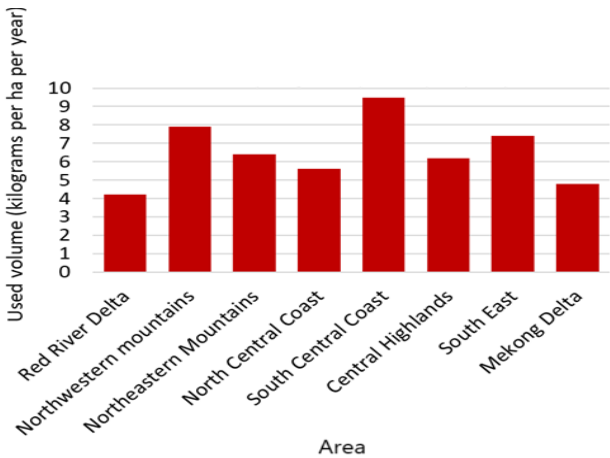

Figure 3. Amounts of pesticides used in cultivation in different areas in Vietnam [48].

A safer and more environmentally friendly alternative to chemical pesticides is the use of biopesticide formulations, which are derived from natural sources such as bacteria, fungi, minerals, or plant-based extracts. Semiochemicals like pheromones are also used to influence pest behavior by attracting them to traps or repelling them from crops. Biopesticides provide a sustainable solution, typically targeting specific pests with minimal harm to non-target organisms. They exhibit less toxicity, quick decomposition, low exposition characteristics, and reduced risks of persistence, bioaccumulation, and environmental toxicity compared to synthetic pesticides [65]. However, as noted by Pan et al. (2023), biopesticides currently represent only a small share of the global crop protection market, around 5%, valued at approximately US$3 billion worldwide [66].

Similar to biofertilizers, Vietnam has also just engaged and researched the production of biopesticides, which are only at the level of products containing beneficial microorganisms that are able to control pathogens on crops, such as preparations containing *Trichoderma*, *Bacillus*, *Streptomyces*, etc. [69].

Bacillus thuringiensis (Bt) can be used as Bt-based biopesticides. In the alkaline gut environment of insects, Bt Cry protoxins are processed by proteases into their active forms. These activated toxins bind to specific receptors on the insect’s gut lining, forming pores that damage cell membranes and ultimately cause the insect’s death [70]. To enhance biological pest control, nanotechnology has been applied in the development of Bt-based biopesticides, resulting in more efficient, stable, and environmentally friendly formulations [66]. Genetically engineered crops, known as plant-incorporated protectants, can produce their own pest resistance. For example, crops modified through *Agrobacterium*-mediated transformation have been engineered to carry Bt genes in their genomes [71]. Additionally, genome editing techniques like CRISPR/Cas systems have been widely used to develop pest-resistant crop varieties [30, 37, 72, 73].

These sustainable and advanced strategies are expected to play a crucial role in integrated pest management by minimizing reliance on external pesticide applications.

3. THE SYNERGY BETWEEN BIOTECHNOLOGY AND ARTIFICIAL INTELLIGENCE

AI has been widely applied in many different fields of biotechnology [74]. In the context of sustainable agriculture, biotechnology provides tools to enhance crop robustness, pest resistance, and resource efficiency. AI can further strengthen these tools by utilizing machine learning (ML). ML uses different methods like supervised learning (learning from labeled data), unsupervised learning (identifying patterns in unlabeled data), and reinforcement learning (learning through trial and error with feedback) and utilizes algorithms to enable computers to identify data patterns, make decisions, and predict outcomes [75].

Advanced genetic engineering can help develop crop varieties that adapt to changing environments, while integrating AI with biotechnology further enhances outcomes, such as optimizing CRISPR applications, developing disease-resistant crops, managing resources such as biofertilizers and biopesticides. Genomics and CRISPR gene editing often involve large-scale data. To minimize off-target effects and reduce screening time, ML algorithms can predict which CRISPR/Cas9 cleavage sites will be cut by a given single-guide RNA (sgRNA) [76, 77]. It is crucial to design and optimize CRISPR/Cas9 editing systems by (1) Optimizing editing efficiency, including (i) predicting the impact of different guide RNAs on editing efficiency and (ii) predicting the impact of different Cas variants on editing efficiency; (2) Optimizing editing specificity, including (i) designing high-specificity guide RNA and (ii) optimizing the editing protein; and (3) Predicting genome editing outcomes [78, 79]; ML also plays an important role in mining the breeding-related genes and detecting the key elements and factors that regulate the expression of these genes; In fact, processes of identifying trait-related genes are often very laborious, because regulatory relationships among genes and their associations to traits are very complicated. Therefore, integration and analysis of multiple omics data with ML techniques can accelerate the process of gene discovery and prioritization, enabling the screening of candidate trait-related genes and their regulatory relationship, to identify potential targets for genome editing [79, 80]. Also, as SynComs allow recognition of stress-responsive genes [61, 62], Figure 4 depicts the process of development of biofertilizers, biopesticides, and high-yield, resilient crop varieties.

In plant science, high-throughput phenotyping (HTP) enables rapid and large-scale trait analysis. When paired with AI and ML, HTP data can uncover patterns and associations between traits like growth, yield, stress tolerance, and disease resistance, and their underlying genetics [81, 82]. Deep learning (DL), a subtype of ML using multi-layered networks such as convolutional neural networks (CNNs) and deep belief networks (DBNs), is particularly effective for image-based plant disease detection [83-88].

AI, integrated with IoT, big data, and cloud computing, supports precision agriculture by simulating plant diversity, selecting effective biofertilizers, identifying suitable microbial strains, and turning complex data into insights on soil, climate, and crop performance [89-94]. Advances in AI-powered technologies, such as drones, robotics, smart irrigation, machine learning for weed detection, and predictive analytics, have improved monitoring accuracy, reduced chemical use, increased yields, lowered labor costs, and enhanced the precision of yield and pest outbreak predictions [92-95].

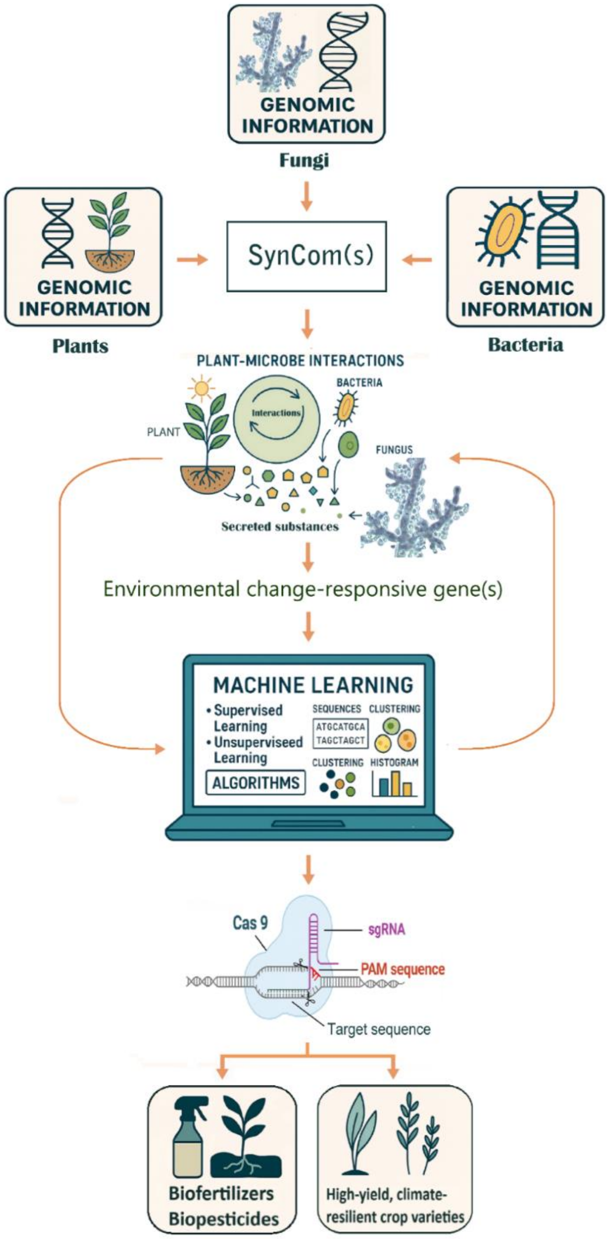

Figure 4. Illustration for integrated-machine learning CRISPR/Cas9 technology in production of biofertilizers, biopesticides, and high-yield, resilient crop varieties.

4. GLOBAL APPLICATIONS OF BIOTECHNOLOGY IN AGRICULTURE

In recent years, the integration of biotechnology and AI has brought major advancements to global agriculture. Biotechnology has made it possible to develop genetically enhanced crops that are more resistant to pests, diseases, and environmental challenges, thereby reducing the need for chemical inputs and boosting productivity. Tools like CRISPR/Cas9 have sped up the development of climate-adapted plant varieties, while microbial-based biofertilizers and biopesticides are being adopted to improve soil health and minimize chemical pollution. At the same time, AI, through machine learning, predictive analytics, and remote sensing, has transformed how crops are monitored, diseases are detected, and resources are managed.

The United Kingdom (UK) stands at the forefront of genomics research, focusing on developing crops that are more resilient to climate change and resistant to diseases, while reducing dependency on chemical inputs. In March 2023, the Genetic Technology (Precision Breeding) Act became law, establishing a regulatory framework for Precision Bred Organisms – organisms with genetic modifications that could also occur naturally or through traditional breeding methods. This legislation, supported by cutting-edge UK research, aims to improve breeding efficiency and produce healthier, more sustainable, and climate-resilient plants and animals [96, 97]. Precision breeding involves genome editing to introduce desirable traits, and the UK joins countries like the United States, Argentina, Australia, etc. in officially supporting this approach.

As of 2022, the United States (U.S.) led global GM crop production with 71.5 million hectares (M ha), mainly cotton, maize, and soybean, followed by Brazil (52.8M ha), Argentina (24M ha), Canada (12.5M ha), and India (11.9M ha) [98]. Bayer and Pairwise used CRISPR to develop less bitter, nutrient-rich mustard greens for the U.S. market, demonstrating gene editing's potential for improved crop traits [99]. U.S. agriculture is also adopting AI-powered precision tools, such as satellite imagery, soil data, and computer vision, for optimized farming, with companies like Farmonaut enhancing accessibility to these innovations [100].

Australia classifies gene-edited crops into SDN-1, SDN-2, and SDN-3, each with distinct regulatory rules [101]. In 2024, InterGrain and Inari companies began CRISPR- and AI-based trials of high-yield wheat strains, aiming for commercial release by 2028. Researchers have also developed nitrogen-efficient barley and wheat using CRISPR/Cas9, enhancing traits like yield, flowering time, and plant height [102]. The Western Crop Genetics Alliance created CRISPR-edited barley with up to 50% more nitrogen uptake and 30% higher yields using less fertilizer, highlighting Australia's push for sustainable, resilient crops [103].

In Canada, gene-edited crops fall under the "Plants with New Traits" regulatory framework, which evaluates the final plant traits rather than the editing technique used [104].

In many African countries, rainfed agriculture and subsistence farming make food systems highly vulnerable to climate change, particularly for crops like banana, which are sensitive to temperature and rainfall shifts. CRISPR/Cas9 has been used to improve stress resistance and nutrition in staple crops, with several nations establishing biosafety regulations [105]. Kenya approved Bt cotton in 2019, boosting seed production by 16% in 2020, and lifted its GMO ban in 2022 to permit Bt maize and virus-resistant cassava, despite some legal delays. The National Biosafety Authority has since approved 58 GMO-related projects [106, 107].

Delays in GM crop adoption have cost Kenya an estimated $157 million, with projected benefits of $467 million over 30 years. After the 2022 court ruling upheld the end of a decade-long GMO ban, Kenya can now advance Bt maize, Bt cotton, and disease-resistant potatoes. The Environment Court's dismissal of a legal challenge cleared the way for GMO cultivation and import, reinforcing scientific consensus on GMO safety and aligning Kenya with at least ten other African nations adopting Bt cotton hybrids for pest resistance [108-110].

Similarly, nations like India and Brazil are integrating AI-driven technologies and biotechnology to boost productivity, reduce environmental impact, and support sustainable agriculture [111, 112].

The integration of biotechnology and AI is transforming global agriculture by boosting yields and sustainability – lessons Vietnam can adopt amid its transition from chemical-dependent farming [113]. To ensure food security and ecological balance, Vietnam needs to expand the use of GM and CRISPR-edited crops, biofertilizers, and biopesticides, which offer higher yields, improved resilience, and reduced chemical reliance. Notable progress includes the 2023 approval of six GM corn hybrids and increasing imports of GM soybeans, corn, and cotton [114]. Since 2015, over 1.3M ha of GM crops have been cultivated, with profits 1.5 to 2 times higher than traditional crops [115]. Advancing gene-editing and AI is crucial to keep pace with global trends. With Resolution No. 68-NQ/TW aiming to strengthen the private sector's economic role by 2030, Vietnam is well-positioned to invest in biotech research, infrastructure, and supportive policies [116, 117].

5. POLICY AND INVESTMENT IN BIOTECNOLOGY FOR AGRICULTURAL TRANSFORMATION

After nearly 40 years of reform, Vietnam has made significant progress toward achieving the United Nations Sustainable Development Goals (SDGs), with agriculture playing a central role [118, 119]. Despite these advancements, the agricultural sector continues to face major challenges, including uneven growth, environmental degradation, shortages of high-quality labor, and low productivity [120]. To overcome these issues, Vietnam is prioritizing scientific research, digital transformation, and the adoption of advanced technologies such as biotechnology and smart agriculture [121].

The country's national action plan supports the development of biotechnology across agriculture, healthcare, and environmental sectors, aiming to position Vietnam among the top ten biotechnology producers in Asia by 2030. By that time, the biotechnology sector is expected to contribute 7% to the national GDP, increasing to as much as 15% by 2045 [122, 123]. To support these goals, Vietnam is also enhancing its legal frameworks and encouraging cross-sector collaboration [124]. Key strategic priorities include building infrastructure, developing a skilled workforce, and strengthening international partnerships. At the same time, the country is promoting eco-friendly, low-carbon, and climate-resilient agricultural practices. Resolutions No. 36-NQ/TW and No. 57-NQ/TW reinforce Vietnam's ambitions to lead in biotechnology by promoting increased investment in science and innovation, and encouraging collaboration in biotechnology and AI [123, 125]. Several policies have been launched to accelerate agricultural biotechnology. These include the Key Program for the Development and Application of Biotechnology in Agriculture and Rural Development (until 2020), the Project on the Development and Application of Biotechnology in Aquaculture (until 2020), and the Project for the Development of Agricultural Biotechnology (until 2030), all aimed at enhancing sustainability and resilience to climate change. Together with legal reforms and initiatives to promote new crop varieties, these efforts are designed to help Vietnam become a regional leader in biotechnology [115].

However, the adoption of biotechnology in Vietnam has been slow, and the gap between Vietnam and the rest of the world is widening. It still faces critical barriers due to policy gaps, regulatory inefficiencies, and implementation challenges. The country has yet to establish dedicated investment policies for biotechnology research infrastructure and funding, and for training specialized human resources. Additionally, there is a need to simplify the registration process for biological products and to develop comprehensive legal frameworks with clear regulations for genome-edited crops – essential steps for ensuring legal certainty and fostering innovation [126-128].

To make research more impactful, investment in research should prioritize outcomes such as biofertilizers, biopesticides, and high-yield, climate-resilient crop varieties. Given ongoing concerns that overreliance on state-run projects may constrain basic research, a more open and collaborative model involving regulators, scientists, and industry is recommended to more effectively translate research into practical applications [115]. Furthermore, the authority to manage and operate specialized biotechnology research facilities should be granted to individuals with deep, field-specific expertise, rather than exclusively to those with high-level academic titles lacking specialized experience in the field. Finally, there should be a mechanism for improving public-private partnerships and increasing commercialization rates to accelerate the translation of research into real-world solutions.

6. CONCLUSIONS

Vietnam's traditional agriculture has heavily depended on chemical fertilizers and pesticides to boost yields and combat crop diseases, seriously affecting human health, polluting the environment and causing ecological imbalance. Transitioning to sustainable agriculture is essential. While the government has issued policies supporting biotechnology and GM crops to enhance resilience and productivity, progress in research and product development remains limited, with underdeveloped infrastructure and human resources. To advance, Vietnam needs to learn from global sustainable agriculture practices and integrate biotechnology with AI to accelerate genetic engineering, improve understanding about plant-microbe interactions for development of gene-edited crops, biofertilizers, and biopesticides. A clear legal framework for innovations like gene editing, increased investment, streamlined regulation, and stronger public-private collaboration are crucial. With these efforts, Vietnam can build a resilient, eco-friendly agricultural sector and position itself as a regional leader in sustainable farming.

Acknowledgement

The author acknowledges Ho Chi Minh City University of Technology (HCMUT), VNU-HCM for supporting this study.

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TÓM TẮT

PHÁT TRIỂN NÔNG NGHIỆP BỀN VỮNG Ở VIỆT NAM VỚI CÔNG NGHỆ SINH HỌC VÀ TRÍ TUỆ NHÂN TẠO

Phan Thị Huyền*

Bộ môn Công nghệ Sinh học, Khoa Kỹ thuật Hóa học, Trường Đại học Bách Khoa,

Đại học Quốc gia, Thành phố Hồ Chí Minh, Việt Nam

*Email: *huyencnshbk@hcmut.edu.vn*

Nông nghiệp Việt Nam đang ngày càng chịu tổn thương trước tác động của biến đổi khí hậu, làm gia tăng cả tần suất lẫn mức độ nghiêm trọng của các bệnh gây hại cây trồng, khiến nông dân gặp nhiều khó khăn trong việc duy trì năng suất. Để ứng phó, phân bón và thuốc trừ sâu có nguồn gốc hóa học đã được sử dụng phổ biến. Tuy nhiên, việc sử dụng quá mức đã gây suy thoái đất, đồng thời làm dấy lên những lo ngại sâu sắc về an toàn thực phẩm, sức khỏe cộng đồng và ô nhiễm môi trường. Trước những thách thức đó, việc chuyển đổi sang một nền nông nghiệp bền vững là yêu cầu cấp thiết, nhằm bảo đảm năng suất và nâng cao khả năng phục hồi của hệ sinh thái. Bài báo này phân tích hướng đi mà nông nghiệp Việt Nam có thể theo đuổi để trở nên bền vững hơn thông qua việc tích hợp công nghệ sinh học và trí tuệ nhân tạo (AI). Công nghệ sinh học cung cấp những giải pháp đột phá giúp giảm sự phụ thuộc vào việc sử dụng các hóa chất độc hại, đồng thời cải thiện chất lượng đất và sức khỏe cây trồng. Khi tích hợp với AI, công nghệ sinh học có thể nâng cao hiệu quả và độ chính xác trong việc phát triển phân bón sinh học, thuốc bảo vệ thực vật sinh học, cũng như các giống cây trồng có năng suất cao và khả năng thích ứng với biến đổi khí hậu. Tham chiếu các mô hình thực tế đã triển khai ở nhiều quốc gia trên thế giới, bài báo làm rõ Việt Nam hoàn toàn có thể áp dụng các công nghệ này để giải quyết các vấn đề nông nghiệp mà Việt Nam đang đối mặt. Việc áp dụng công nghệ sinh học với các giải pháp được tăng cường hiệu quả và độ chính xác bởi trí tuệ nhân tạo vào nông nghiệp có tiềm năng chuyển đổi nền nông nghiệp Việt Nam thành một nền nông nghiệp hiện đại, thân thiện với môi trường, hài hòa giữa năng suất và tính bền vững. Tuy nhiên, để hiện thực hóa sự chuyển đổi này, cần có sự đầu tư mạnh mẽ vào nghiên cứu và hạ tầng kỹ thuật công nghệ sinh học, vào đào tạo và phát triển nguồn nhân lực có trình độ chuyên môn cao, song song với việc thiết lập hành lang pháp lý đầy đủ và rõ ràng để bảo trợ cho các tiến trình đổi mới và sáng tạo. Thông qua việc học hỏi kinh nghiệm quốc tế và điều chỉnh linh hoạt theo điều kiện trong nước, Việt Nam có thể kiến tạo một nền nông nghiệp vững bền và thích ứng hiệu quả, đảm bảo an ninh lương thực và bảo vệ môi trường trong bối cảnh khí hậu biến đổi ngày càng gay gắt.

Từ khóa: Công nghệ sinh học nông nghiệp, trí tuệ nhân tạo, phân bón sinh học, thuốc trừ sâu sinh học, CRISPR/Cas9, nông nghiệp bền vững.