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# ROLE OF BIOTECHNOLOGY IN SUSTAINABLE AGRICULTURAL DEVELOPMENT IN THE MEKONG DELTA

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## ABSTRACT

*Sustainable agricultural development in the Mekong Delta faces significant challenges, including water scarcity due to prolonged droughts, salinity intrusion from rising sea levels, soil degradation, and increased pest and disease prevalence. These issues threaten agricultural productivity and food security, impacting the livelihoods of local communities. Biotechnology, with its diverse applications, has emerged as a promising avenue to address these pressing issues. This comprehensive review article examines the multifaceted role of biotechnology in fostering sustainable agricultural development in the Mekong Delta. It delves into the potential of genetic engineering, microbial technology, and precision farming to improve crop yields, enhance nutrient use efficiency, and develop climate-resilient crop varieties. The review also explores the application of biotechnology in livestock and aquaculture management, pest and disease control, and the valorization of agricultural waste, highlighting their contributions to environmental conservation and resource optimization. Furthermore, the article discusses the societal and policy implications of integrating biotechnology into the regional agricultural landscape, considering aspects of food security, equitable access, and community engagement. By synthesizing the current state of knowledge, this review provides a holistic understanding of the transformative role of biotechnology in shaping a more sustainable and resilient agricultural future for the Mekong Delta.*

## 1. INTRODUCTION

The Mekong Delta, a vast and fertile region located in the southern part of Vietnam, has long been recognized as the "rice bowl" of the country, contributing significantly to national and global food security. However, this agricultural powerhouse faces a confluence of challenges that threaten the sustainability of its food production systems. Climate change, manifested through rising sea levels, increased salinity intrusion, and more frequent extreme weather events, poses a significant threat to the region's crop productivity and resilience (Smajgl et al., 2015; Toan, 2014; Hai et al., 2024). Additionally, environmental degradation, driven by factors such as excessive fertilizer and pesticide use, as well as the overexploitation of natural resources, has led to soil depletion, water pollution, and the loss of biodiversity (Le et al., 2023).

In the face of these daunting challenges, the need for innovative solutions to ensure sustainable agricultural development in the Mekong Delta has become increasingly evident. Sustainable agricultural development refers to an integrated approach to farming that aims to enhance agricultural productivity while protecting the environment and ensuring the long-term viability of the region's natural resources (Muhie, 2022). Efficient irrigation systems and practices that minimize water waste are essential, especially in regions facing water scarcity. Practices that enhance soil fertility and structure, such as cover cropping and reduced tillage, are critical for maintaining long-term agricultural productivity. Farmers need access to modern agricultural technologies, including precision agriculture tools, to improve yields while minimizing environmental impacts (Karunathilake et al., 2023). Training programs to educate farmers about sustainable practices, resource management, and new technologies are vital for successful implementation,...Biotechnology, with its diverse applications in the agricultural sector (Ranjha et al., 2022), has emerged as a promising avenue to address these pressing issues. By harnessing the power of genetic engineering, microbial technology, and precision farming, biotechnology has the potential to enhance crop yields, improve resource use efficiency, and develop climate-resilient agricultural systems (Das et al., 2023) (Figure 1).

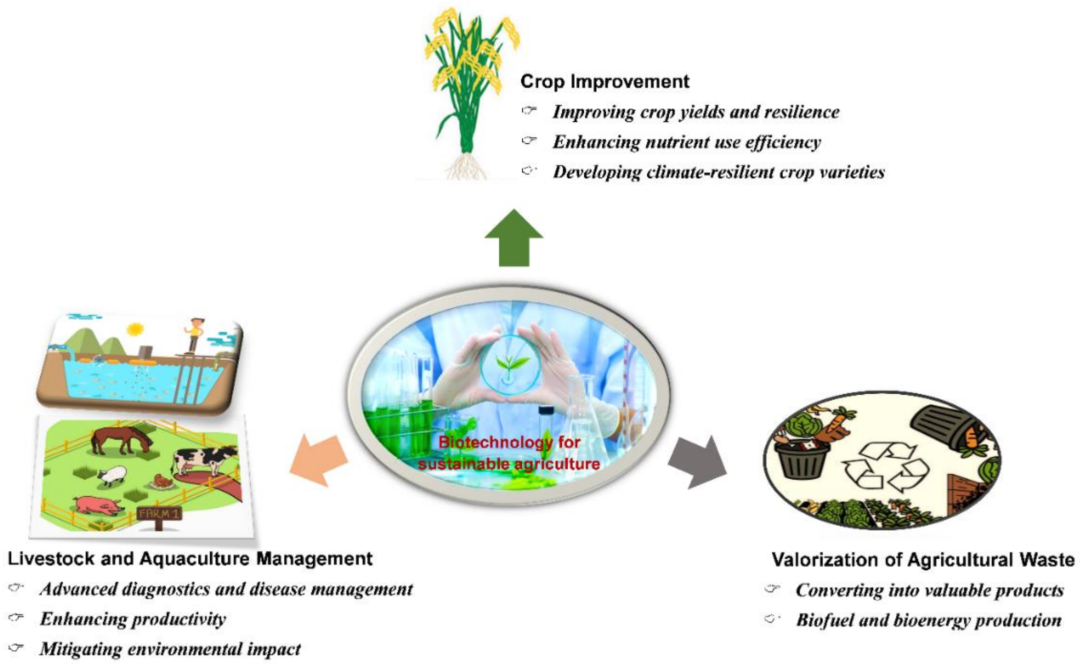


**Figure 1. Role of biotechnology in sustainable agricultural development**

This comprehensive review article aims to explore the multifaceted role of biotechnology in fostering sustainable agricultural development in the Mekong Delta. It will delve into the potential of biotechnological interventions to address the region's unique challenges, while also considering the societal and policy implications of their integration into the agricultural landscape.

## 2. CROP IMPROVEMENT THROUGH BIOTECHNOLOGY

The Mekong Delta faces a range of difficulties in agricultural production that are influenced by natural factors. Prolonged dry spells can lead to water scarcity, affecting crop yields, particularly for water-intensive crops like rice. Additionally, reduced river flows and groundwater levels can exacerbate drought conditions, threatening both agriculture and local livelihoods (Minh et al., 2024). Rising sea levels and diminished freshwater flow can result in salinity intrusion, particularly in coastal areas, which adversely affects crop growth and reduces agricultural productivity. Moreover, salinity can lead to soil degradation, rendering previously arable land less suitable for cultivation (Smajgl et al., 2015). The prevalence of pests and diseases also poses a significant threat to crop production. Warmer temperatures and changing rainfall patterns can intensify these challenges (Nguyen et al., 2022). Addressing these issues necessitates a comprehensive approach, with biotechnology serving as a key strategy to mitigate these challenges. By leveraging biotechnological innovations, it is possible to develop resilient crop varieties, improve resource management, and enhance overall agricultural sustainability in the Mekong Delta.

### *2.1 Improving crop yields and resilience*

The Mekong Delta's agricultural productivity has historically been high, with rice being the primary staple crop. However, the region's susceptibility to climate change-induced threats, such as saltwater intrusion, drought, and flooding, has threatened crop yields and overall food security (Smajgl et al., 2023; Kang et al., 2021). Biotechnology offers solutions to address these challenges through the development of genetically engineered crop varieties with improved stress tolerance and yield potential. One notable example is the development of salt-tolerant rice cultivars The Saltol gene, a major quantitative trait locus (QTL) for salt tolerance, is being transferred into seven popular locally adapted rice varieties, including ADT45, CR1009, Gayatri, MTU1010, PR114, Pusa 44, and Sarjoo 52 (Singh et al., 2016). Additionally, the constitutive overexpression of the vacuolar $Na^+/H^+$ antiporter gene (OsNHX1) from the rice landrace Pokkali has been employed to enhance salt tolerance in transgenic rice plants (Amin et al., 2016). These genetically modified rice plants demonstrate enhanced tolerance to high salinity levels, allowing them to thrive in the face of saltwater intrusion, a growing problem in the Mekong Delta. Field trials have shown that these salt-tolerant rice varieties can maintain yield levels even in areas with high soil salinity (Mheni et al., 2024), making them a valuable resource for farmers in the region. Similarly, biotechnology has been employed to develop flood-tolerant rice cultivars. By introducing genes from deepwater rice varieties that can rapidly elongate their stems in response to flooding, researchers have created rice plants that can survive and continue to grow under submerged conditions (Haque et al., 2023). This adaptation is particularly crucial for the Mekong Delta, where seasonal flooding is a common occurrence and a key contributor to agricultural productivity.

In addition to abiotic stress tolerance, biotechnology has also been used to improve crop resistance against biotic stresses, such as pests and diseases. The introduction of genes encoding insecticidal proteins from the bacterium Bacillus thuringiensis into various crops, including rice, has resulted in enhanced resistance to major insect pests, reducing the need for excessive pesticide application (Li et al., 2023). This not only benefits the environment by reducing chemical inputs but also improves the economic viability of farming operations in the Mekong Delta.

### *2.2 Enhancing nutrient use efficiency*

Another significant contribution of biotechnology to sustainable agricultural development in the Mekong Delta is the enhancement of nutrient use efficiency in crops. Excessive and indiscriminate use of chemical fertilizers has led to environmental degradation, water pollution, and greenhouse gas emissions in the region (Tho & Umetsu, 2022; Sebesvari et al., 2012). Biotechnological approaches, such as the engineering of crops with improved nitrogen and phosphorus uptake and utilization, can help address these challenges.

Researchers have developed genetically modified rice varieties with increased expression of genes involved in nitrogen assimilation and translocation. These enhanced rice plants can more efficiently absorb and utilize available nitrogen, reducing the need for excessive fertilizer application (Li et al., 2020). Similarly, the introduction of genes responsible for the production of phosphate-solubilizing enzymes has enabled crops to better access inorganic phosphorus from the soil, thereby improving phosphorus use efficiency (Wu et al., 2013).

The integration of these biotechnology-derived crops into the Mekong Delta's agricultural systems can contribute to a more sustainable and resource-efficient farming model, reducing the environmental footprint of agricultural activities while maintaining high productivity levels.

### *2.3 Developing climate-resilient crop varieties*

The Mekong Delta's vulnerability to climate change-induced threats, such as rising temperatures, altered precipitation patterns, and increased frequency of extreme weather events, necessitates the development of crop varieties that can thrive in these challenging conditions. Biotechnology has played a pivotal role in this regard, enabling the creation of climate-resilient crop cultivars.

As global warming intensifies, it presents significant challenges to rice production, with frequent occurrences of heat stress emerging as one of the most critical meteorological factors limiting yield (Xie et al., 2023). Researchers have identified and transferred genes that confer improved tolerance to high temperatures, allowing rice plants to maintain productivity even under conditions of elevated thermal stress (Ye et al., 2021). These heat-tolerant rice cultivars can help mitigate the impact of rising temperatures on crop yields in the Mekong Delta, where temperature extremes are becoming more prevalent.

Likewise, biotechnology has been employed to develop drought-tolerant crop varieties. By introducing genes that regulate water use efficiency, osmotic adjustment, and root architecture, scientists have created crop plants that can better withstand prolonged periods of water scarcity (Panda et al., 2021; Chengqi et al., 2024). These drought-resilient cultivars can contribute to the region's resilience in the face of erratic rainfall patterns and extended dry spells.

The development of climate-resilient crop varieties through biotechnology not only enhances the Mekong Delta's agricultural productivity but also improves the long-term sustainability of the region's food production systems by reducing their vulnerability to the adverse impacts of climate change.

### *2.4 Pest and disease control through biotechnology*

Pests and diseases pose a significant threat to the agricultural productivity and sustainability of the Mekong Delta. Conventional pest control methods, which often rely heavily on the use of synthetic pesticides, have raised concerns about their environmental impact, human health risks, and the development of pesticide resistance in target organisms. Biotechnology has emerged as a promising alternative, offering innovative solutions for integrated pest and disease management in the Mekong Delta. One of the key biotechnological approaches is the development of biopesticides, which utilize naturally occurring microorganisms or their derived compounds to control pests and diseases. For instance, the use of Bacillus thuringiensis biopesticides has gained traction in the Mekong Delta. Several commercially available products in the market include Vi-BT 32000WP, Vi-BT 16000WP, BT Xentary 35WDG, and Firibiotox in both powder and concentrated liquid forms (Plant Protection Department, 2014). Bacillus thuringiensis is a soil-dwelling bacterium that produces insecticidal proteins, which can be formulated into effective and environmentally friendly biopesticides. These Bacillus thuringiensis-based products have been successfully deployed against major insect pests of crops, such as rice stem borers and fruit flies, without the adverse effects associated with synthetic pesticides (Azizoglu et al., 2023).

Another biotechnological approach to pest and disease control is the use of gene-editing techniques, such as CRISPR-Cas9, to develop crop varieties with enhanced resistance. By targeting and disabling genes responsible for susceptibility to specific pathogens or pests, researchers have created crop plants that can better withstand disease and pest pressure, reducing the need for chemical interventions (Ray et al., 2023). Furthermore, biotechnology has enabled the development of early warning systems and precision monitoring tools for pest and disease outbreaks. The integration of advanced diagnostic techniques, including DNA-based detection and remote sensing technologies, allows for the rapid identification and targeted management of emerging threats, facilitating a more proactive and sustainable approach to crop protection (Negi & Anand, 2024).

## 3. BIOTECHNOLOGY IN LIVESTOCK AND AQUACULTURE MANAGEMENT

Beyond crop improvement, biotechnology has also made significant contributions to the sustainable management of livestock and aquaculture in the Mekong Delta (Figure 1). The region's livestock and aquaculture sectors play an important role in supporting the livelihoods of smallholder farmers and contributing to food security, but it also faces various challenges related to animal health, productivity, and environmental impact.

### *3.1 Advanced diagnostics and disease management*

Biotechnology has significantly advanced the health and productivity of livestock and aquaculture in the Mekong Delta. The development of sophisticated diagnostic tools and targeted therapeutic interventions has played a crucial role in this process. The application of molecular techniques, such as PCR-based pathogen detection and serological assays, has facilitated the early and accurate identification of animal diseases. This capability allows for more effective disease prevention and control measures (Malik et al., 2020). Breeding strategies have also proven effective in preventing infectious diseases in both livestock and aquaculture. For instance, genetically engineered pigs expressing short hairpin RNA (shRNA) have demonstrated enhanced resistance to the virus responsible for foot-and-mouth disease (Hu et al., 2021). Additionally, selective breeding has been extensively utilized to improve disease resistance in key aquaculture species (Potts et al., 2021). Another example in aquaculture is the use of genetic selection and molecular breeding techniques to develop whiteleg shrimp that are resistant to common viral pathogens, such as White Spot Syndrome Virus (WSSV) (Lillehammer et al., 2020). While there is significant potential for mollusks, the commercial application of these methods remains in the early stages of development.

The use of recombinant DNA technology has led to the creation of improved vaccines against prevalent livestock diseases in the region, such as foot-and-mouth disease, avian influenza, and classical swine fever (Aida et al., 2021). These genetically engineered vaccines have demonstrated enhanced efficacy and safety profiles, contributing to the overall health and well-being of livestock populations in the Mekong Delta (Huynh et al., 2019; Lam & Le, 2023). In aquaculture, vaccination is also an important aspect. Vaccines developed using advanced molecular techniques represent an effective approach to combatting disease-causing pathogens in aquatic organisms (Mondal & Thomas, 2022).

### *3.2 Enhancing productivity through biotechnology*

In addition to disease management, biotechnology has also been employed to enhance the productivity of livestock and aquaculture. Through the application of techniques like marker-assisted selection and genome editing, researchers have identified and introduced genetic traits that can improve performance, such as increased growth rates, feed efficiency, and milk or egg production (Schultz et al., 2020). The advancements in genetic engineering and gene editing technologies, particularly CRISPR/Cas9, represent significant progress in aquaculture. These innovative approaches enable precise modifications that can enhance growth, nutritional content, and reproductive management of key aquaculture species, contributing to the sustainability and productivity of the industry (Sahoo & Paul, 2023). These biotechnology-driven advancements have the potential to boost the overall productivity and economic viability of the livestock and aquaculture sectors in the Mekong Delta.

### *3.3 Mitigating environmental impact*

The livestock sector in the Mekong Delta, like in many other regions, is a significant contributor to environmental challenges, such as greenhouse gas emissions, water pollution, and waste management issues. Biotechnology offers solutions to address these concerns and promote more sustainable livestock production practices. One area where biotechnology has made notable contributions is in the development of feed additives and supplements that can reduce methane emissions from ruminant livestock, such as cattle and buffaloes. The introduction of genes encoding methanogen-inhibiting enzymes or the incorporation of microorganisms with methane-oxidizing capabilities into animal feed can help mitigate the greenhouse gas footprint of livestock production (Gerber et al., 2013). Additionally, biotechnology has been employed to improve the nutritional value and digestibility of livestock feed, reducing the amount of unutilized nutrients excreted as waste. The engineering of enzymes that can break down recalcitrant plant polysaccharides, for instance, can enhance the bioavailability of nutrients in animal feed, thereby improving nutrient use efficiency and minimizing the environmental impact of livestock waste (Plouhinec et al., 2023). Moreover, biotechnology has enabled the development of innovative waste management solutions for the livestock sector in the Mekong Delta. The use of microbial technology to convert animal waste into biofuels, biofertilizers, and other value-added products has the potential to transform livestock waste from an environmental liability into a resource (Arora et al., 2021). This circular approach to livestock waste management can contribute to the overall sustainability of the sector.

Aquaculture is a rapidly growing industry that plays a significant role in global food production. However, it also poses environmental challenges, including water pollution, habitat destruction, and the overuse of antibiotics (Collier et al., 2016). Biotechnology offers innovative solutions to mitigate these impacts, promoting sustainable practices that enhance both productivity and ecological health. In response to these pressing concerns, there is a growing recognition of the need to explore alternative approaches to aquaculture that are more environmentally sustainable and resilient. One such approach is the development of integrated multi-trophic aquaculture (IMTA) systems, which combine the cultivation of different aquatic species, such as shrimp, seaweed, and microalgae, to create synergistic relationships and optimize resource utilization (Kamleshbhai et al., 2023). Biotechnology also plays a crucial role in improving feed efficiency. The use of enzyme supplementation and formulation innovations enhances the digestibility of feed (Liang et al., 2022). This improvement leads to reduced waste production and minimizes nutrient runoff into aquatic environments, thereby decreasing the potential for water pollution. In addition, the utilization of microorganisms for the treatment of waste and pollutants in aquaculture systems is gaining attention (Li et al., 2022). Bioremediation techniques can effectively clean contaminated water, reducing the environmental footprint of aquaculture operations (Dhar et al., 2023). By employing biological methods to manage waste, aquaculture can become more sustainable and minimize reliance on chemical interventions.

## 4. VALORIZATION OF AGRICULTURAL WASTE THROUGH BIOTECHNOLOGY

The Mekong Delta, with its thriving agricultural activities, generates significant amounts of organic waste, including crop residues, animal manure, and processing byproducts. A triple-rice-cropping system is prevalent in the Mekong Delta, resulting in the production of approximately 21 million tons of rough rice annually (as of 2008), alongside an estimated 24 million tons of dry straw mass generated each year (Arai et al., 2014). In livestock production, manure management is the largest contributor to methane ($CH_4$) emissions, one of the major greenhouse gases. Specifically, total $CH_4$ emissions from livestock waste management activities (dairy and beef cows) in the Mekong Delta were reported to be 1,286 tons per year (GSO, 2015). In terms of processing byproducts, for example, Vietnam’s Tra Catfish (Pangasius sp.) industry in the Mekong Delta has been reported to produce approximately 1.42 million tons in recent years. Catfish processing byproducts constitute more than 60-70% of the total fish biomass, excluding blood and water-soluble protein fractions (VASEP, 2019). Traditionally, the management of this waste has posed environmental and economic challenges, with improper disposal leading to pollution, greenhouse gas emissions, and the loss of valuable resources. Biotechnology has emerged as a transformative solution for the valorization of agricultural waste in the Mekong Delta (Figure 1), enabling the conversion of these byproducts into valuable biobased products and energy sources (Bala et al., 2023) (Table 1).

One of the key applications of biotechnology in this domain is the use of microbial technology for the production of biofuels and bioenergy. Through the process of anaerobic digestion, microorganisms can convert organic waste, such as rice straw, sugarcane bagasse, and animal manure, into biogas rich in methane (Gupta et al., 2022). This biogas can then be utilized for heat and electricity generation, providing a renewable energy source and reducing the reliance on fossil fuels. Furthermore, biotechnology has facilitated the development of advanced bioremediation techniques for the treatment of agricultural wastewater. By leveraging the metabolic capabilities of specific microorganisms, researchers have created systems that can effectively remove and recover nutrients, heavy metals, and other pollutants from water bodies affected by agricultural runoff (Reddy et al., 2024; Huang et al., 2021). This not only improves the quality of water resources but also enables the valorization of the extracted nutrients and minerals for use as biofertilizers.

**Table 1. Certain scalable options to enhance the value of agricultural waste**

| Management approach | Discussion | References |
| --- | --- | --- |
| Biofuels production | Producing biofuels from biodegradable waste, agricultural residues or straw (lignocellulosic biomass) to help mitigate many environmental problems and global scenarios such as global warming, greenhouse gas emissions, meeting global energy demand, etc. | (Sharma et al., 2020) |
| Biopesticides | The increasing demand for sustainable agricultural practices has prompted the exploration of biopesticides as an effective alternative to conventional chemical pesticides. Agricultural waste, which encompasses a significant volume of non-edible residues generated from crop cultivation and processing, presents an opportunity to produce biopesticides while simultaneously addressing waste management issues. | (Kumar et al., 2024) |
| Production of mushrooms | The primary requirements for mushroom cultivation include rice straw, spawn, labor, and water. The net yield is approximately 0.8 kg of mushrooms per 10 kg of dried straw, resulting in a profit ranging from $50 to $100 per ton of straw. | (Thuc et al., 2020) |
| Vermicomposting | Vermicomposting provides an effective means for microbes and earthworms to collaborate in the degradation of waste and the enrichment of nutrients. Due to its environmentally friendly nature, vermicomposting is widely employed worldwide to decompose various organic materials into sustainable products. | (Lirikum et al., 2022) |
| Composting | Composting is an effective method for managing agricultural waste, transforming organic materials into nutrient-rich compost that can enhance soil health and fertility. | (Waqas et al., 2023) |
| Bioactives and bioproducts | The transformation of agro-waste into value-added bioproducts and bioactive compounds presents a sustainable solution to waste management while contributing to economic growth. By harnessing innovative bioconversion processes, agro-waste can | (Rai & Choure, 2023; Bala et al., 2023) |

be effectively repurposed, leading to enhanced environmental sustainability and the development of beneficial products across various industries.

In addition to bioenergy and bioremediation, biotechnology has also enabled the conversion of agricultural waste into value-added biomaterials and biochemicals. The enzymatic or microbial transformation of cellulose, hemicellulose, and lignin from crop residues can yield a wide range of products, including bioplastics, biobased chemicals, and platform chemicals for further industrial applications (Mujtaba et al., 2023). These biotechnology-driven initiatives can create new income streams for farmers and processors, while simultaneously promoting a more circular and sustainable agricultural economy in the Mekong Delta.

## 5. SOCIETAL AND POLICY IMPLICATIONS

The integration of biotechnology into the agricultural landscape of the Mekong Delta has profound societal and policy implications that must be carefully considered to ensure the equitable and sustainable deployment of these technologies.

### *5.1 Food security and accessibility*

The Mekong Delta contributes over half of Vietnam’s rice production and 90% of its rice exports annually (Tho & Umetsu, 2022). Therefore, one of the primary concerns regarding the role of biotechnology in sustainable agricultural development is its impact on food security and accessibility. While the enhanced productivity and resilience of biotechnology-derived crops and livestock can contribute to increased food availability (Tyczewska et al., 2023), the accessibility and affordability of these products for smallholder farmers and low-income communities must be addressed. Policymakers in the Mekong Delta region must implement measures to ensure that the benefits of biotechnological innovations are equitably distributed, addressing issues of intellectual property rights, technology transfer, and subsidies for resource-poor farmers. Inclusive policies and investment in agricultural extension services can empower smallholder farmers to adopt and benefit from biotechnology-based solutions, strengthening food security at the local level.

### *5.2 Environmental conservation and ecological integrity*

The integration of biotechnology into the Mekong Delta's agricultural systems must also be accompanied by robust environmental safeguards to preserve the region's delicate ecological balance. Concerns regarding the potential impacts of genetically modified organisms on biodiversity (Nawaz et al., 2020), soil health, and water resources (Wheatley, 2009) must be carefully evaluated and managed through comprehensive risk assessment and monitoring frameworks. Policymakers should prioritize the development of regulatory mechanisms that ensure the responsible and sustainable deployment of biotechnological applications, balancing the benefits of increased productivity with the need to maintain the integrity of the natural environment. This may involve the establishment of biosafety protocols, environmental impact assessments, and stakeholder engagement processes to address the concerns of local communities and environmental advocates.

### *5.3 Stakeholder engagement and capacity building*

The successful integration of biotechnology into sustainable agricultural development in the

Mekong Delta requires the active engagement and capacity building of diverse stakeholders, including farmers, industry, academia, and policymakers. Comprehensive stakeholder engagement programs should be implemented to foster dialogue, address concerns, and facilitate the co-creation of biotechnology-based solutions that align with the region's unique social, cultural, and environmental contexts. Capacity-building initiatives, such as training programs and knowledge-sharing platforms, can empower farmers and local communities to understand, adopt, and benefit from biotechnological advancements. Furthermore, interdisciplinary collaboration between researchers, industry, and policymakers can catalyze the development of innovative biotechnology applications that are tailored to the specific needs and challenges of the Mekong Delta. This collaborative approach can ensure that biotechnology-driven solutions are contextually relevant, socially acceptable, and environmentally sustainable.

## 6. CONCLUSION

The Mekong Delta, a region renowned for its agricultural prowess, faces a confluence of challenges that threaten the sustainability of its food production systems. In the face of these daunting challenges, biotechnology has emerged as a transformative force, offering a diverse array of solutions to enhance crop productivity, improve livestock management, and valorize agricultural waste. Through the development of genetically engineered crops with enhanced stress tolerance, nutrient use efficiency, and climate resilience. Furthermore, biotechnology enables the creation of diagnostic and therapeutic tools aimed at improving animal health and productivity. Additionally, biotechnology provides promising alternatives for integrated pest and disease management, as well as strategies for enhancing the value of agricultural waste. The integration of biotechnology into agricultural practices in the Mekong Delta carries significant implications. To ensure the successful implementation of these biotechnological advancements, collaboration among various stakeholders including farmers, industry representatives, academia, and policymakers is essential. This collective effort will facilitate the development of sustainable agricultural practices that can effectively address the challenges faced by the region.

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