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ABSTRACT: Recently, China released its first 5-year plan for bioeconomy development, in which bioagriculture was identified as one of the five key development areas. It not only aims to cultivate new momentum for ensuring food security in China but also outlines a new direction for agro-biotechnology innovation and the development of the bioindustry. This paper elaborates on the significance of agriculture as a crucial application scenario in the future bioeconomy and analyzes the demand for agricultural biotechnology in the context of China's food security. Additionally, it summarizes the development experiences of countries and regions, such as the United States and the European Union in the field of bioeconomy, including their strategic policies, leading technologies, and policy impacts. The paper further proposes specific ways to fully leverage the supportive role of bioeconomy in ensuring China's food security. These methods encompass the enhancement of agricultural biotechnology innovation capabilities, the application of biotechnological achievements in agriculture, and the refinement of the regulatory framework for biotechnology.

KEYWORDS: *bioeconomy, agriculture, biotechnology, food security, application scenarios, policy implications*

1. INTRODUCTION

To ensure food security and establish a robust agricultural sector, China urgently requires technological support, especially in the realm of biotechnology. President Xi Jinping emphasized at the Central Rural Work Conference that "as China moves toward its second centennial goal, successfully achieves poverty alleviation, and confronts challenges arising from the ongoing COVID-19 pandemic and global uncertainties, it is imperative to concentrate on consolidating and expanding the achievements in poverty alleviation, promoting rural revitalization comprehensively, and accelerating the modernization of agriculture and rural areas. These objectives demand the undivided attention of the entire party".[1] In 2023, the no. 1 central document of the Central Committee of the Communist Party of China (CPC) first proposed the ambition to build a robust agricultural nation and reiterated the imperative to "resolutely safeguard food security".[2] The role of agriculture in the new era is expanding beyond the mere provision of agricultural products and raw materials for upstream industrial chains; it now includes aspects such as leisure tourism and ecological conservation. In the future, it is expected to evolve into a comprehensive agricultural system encompassing biological subsystems related to nutrition and health, resources, energy, and ecological environments.[3] The concept of food security continues to evolve, requiring comprehensive considerations of quantity security, nutritional security, capacity security, and ecological security. Furthermore, enhancing food security levels necessitates adhering to the principle of balancing resource acquisition and cost reduction, striving for increased production, while minimizing losses. Promoting the application of biotechnology in the agricultural sector is an important way to achieve multiple goals of food security, promote conservation and loss reduction, and realize the multiple functions of modern agriculture.

Currently, more than 60 countries have introduced macro-level strategies and implementation plans aimed at fostering the growth of the bioeconomy.[4] However, there is no globally standardized definition of the bioeconomy. From the perspective of productivity, the bioeconomy primarily relies on research, development, and application of life sciences and biotechnology, representing a novel economic paradigm distinct from both industrial and information economies. From the perspective of production relations, it takes the form of a composite economy dedicated to achieving sustainability through the production, distribution, and consumption of biotechnology products, fostering connections across various industry chains.[5,6] At the beginning of this century, the United States (US) took the lead in proposing the development of the bioeconomy, followed closely by the European Union (EU). However, China started relatively late in the field of

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bioeconomy. The development of the bioeconomy in the US primarily focuses on rapid economic growth, while developed countries in the EU, represented by Germany, emphasize environmental sustainability. In May 2022, China unveiled its inaugural 5-year plan for bioeconomic development, officially known as the "14th Five-Year Plan for the Development of the Bioeconomy" (referred to as the "Plan" hereafter).[7] The Plan designates agriculture as one of the five main application domains, emphasizing the development of new-generation agricultural bioproducts, particularly in the areas of biological breeding, biological fertilizers, biological pesticides, and biological feed.

In some developed countries, bioeconomy has been proven to have significant economic, social, and environmental benefits and play an important role in promoting high-quality agricultural development and ensuring food security. For example, the EU's bioeconomic sector contributed 34 million euros to the added value of the agricultural industry between 2008 and 2019.[8] In the nearly 50 years since the first genetic engineering experiment, the bioeconomy generated at least 5.1% of the US GDP, with more than half of the total generated by the agricultural and industrial biotechnology sectors.[9] China's bioeconomy is also experiencing rapid development. As for 2020, the output value of sectors such as biopharmaceuticals, biomanufacturing, biobreeding, bioenergy, and bioenvironmental protection in China has approached nearly 5 trillion RMB. The main business revenue of the bio and health industry exceeded 10 trillion RMB.[10] However, the policy framework for China's bioeconomy is still in its nascent stage, and there is an urgent need to draw up the experience of other countries with mature developments in the field of bioeconomy.

This paper aims to explore a pathway to promote the development of China's bioeconomy, thereby ensuring food security. It analyzes the demand for biotechnology and bioeconomy to ensure food security and posits that agriculture will be one of the important application scenarios for China's future bioeconomy and also one of the core pillars of the bioeconomy. What's more, this paper summarizes the development history of bioeconomy in representative countries and summarizes relevant experiences from the latest policies, leading technologies to social, economic, and environmental benefits assessment. Based on these findings, we propose strategies to refine the policy framework of China's bioeconomy and foster rapid advancements in bioagriculture in China. The research outcomes hold significant implications for accelerating the development of China's agricultural bioeconomy, thereby ensuring food security in the new era.

2. NECESSITY FOR THE DEVELOPMENT OF BIOAGRICULTURE IN CHINA

2.1. Background and Current Status of Bioagriculture in China. Agriculture holds a fundamental position in China's national economy. According to the China Statistical Yearbook (2022), the total output value of agriculture, forestry, animal husbandry, and fishing in China reached 17.7 trillion yuan in 2021, accounting for 12.85% of the total GDP. Biotechnology has greatly improved the efficiency of agricultural breeding and the protection and utilization of germplasm resources. Traditional breeding methods are gradually being supplanted by biotechnology-driven breeding techniques. Biological breeding technology plays an important role in ensuring the supply of critical agricultural products, such as food and feed, by improving the crop yield, quality, and stress resistance. By 2020, China had successfully developed 188 varieties of insect-resistant cotton, commanding a market share of more than 99% within the country. This achievement translated into economic benefits exceeding 50 billion yuan.[11] At the same time, the development goals of agriculture in the new era have undergone a historic turning point, shifting toward a focus on bioagriculture characterized by the widespread application of biotechnology and the boom of biological products. China's bioagriculture spans various sectors, including biological breeding, biological fertilizers, biological feed, and biological pesticides, contingent on the distinct fields of biotechnological application. While not experiencing the same rapid growth as biotechnology in sectors such as bioenergy and biopharmaceuticals, bioagriculture has assumed a significant position within the bioeconomy of the US and the EU. The US agricultural sector alone generates an annual biomass production exceeding one billion tons, whereas the EU has prioritized synergizing with other policies, notably the Common Agricultural Policy, to propel the growth of the bioeconomy in agricultural and rural settings.[12]

The development of bioagriculture in China is still in its nascent stage, yet it holds immense significance in advancing high-quality agricultural development in the new era. The food demand of Chinese residents has shifted from "solving basic needs" to "nutritional diversity". Thus, the development of bioagriculture needs to meet the new expectations of the people for higher levels of food consumption. China's agricultural production is facing problems such as excessive fertilizer and pesticide usage, which poses challenges for the sustainable development of agriculture. In recent years, China has successively issued policies to reduce the application of pesticides and fertilizers, resulting in a reduction from a peak of 1.81 million tons in 2013−1.39 million tons in 2019 (a decrease of 23.01%) for pesticides and a year-on-year decrease from a peak of 60.22 million tons in 2015−54.03 million tons in 2019 (a decrease of 10.28%) for fertilizers. Nevertheless, China's pesticide and fertilizer application rates remain 2−3 times higher than those in leading agricultural nations like the US and Brazil.[13] The proportion of China's agricultural product processing output value to the total agricultural output value remains strikingly low, and the extension of the agricultural industry chain remains at a rudimentary stage. The application of biotechnology and the development of bioeconomy in the agriculture sector can effectively tackle issues such as insufficient crop yields, pesticide and fertilizer pollution, and unsustainable resources from the source. At the same time, the growth of the bioeconomy can promote technological innovation and industrial cultivation in agriculture and rural areas and generate a large number of employment opportunities.[14] For example, Germany's bioagriculture has successfully achieved the objective of one farmer supporting hundreds of individuals and has created over 1 million job opportunities across the entire industrial chain.[15]

2.2. Demand for Bioagriculture in Ensuring China's Food Security. Ensuring food security is the primary task of agricultural development in China's new era, and the development of bioagriculture is an important channel for ensuring food security. The concept of food security in China's new era continues to evolve, requiring a comprehensive and coordinated approach to address quantity security, nutritional security, capacity security, and ecological security as well. The development of the bioeconomy offers viable solutions for

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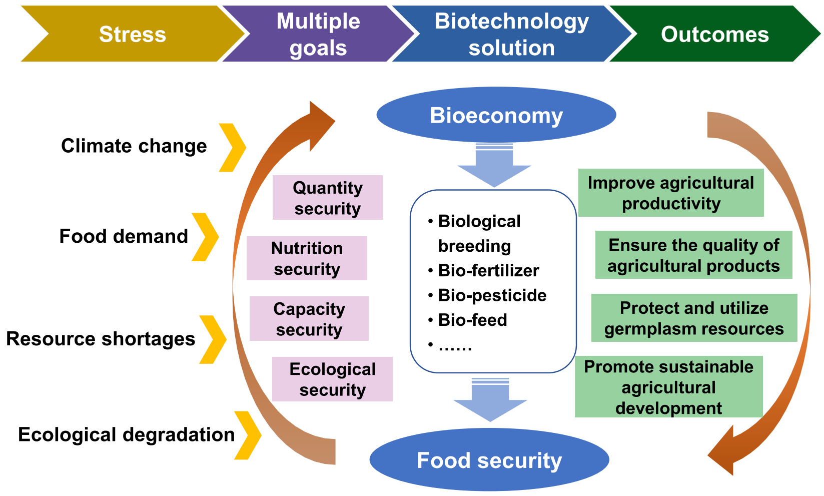

Figure 1. Bioeconomy provides a path to ensure food security.

attaining these diverse food security goals. With the development of the social economy, the food consumption of Chinese residents is increasingly upgrading, shifting from solving basic needs to diversified nutrition. Therefore, China's food demand is constantly increasing, and structural contradictions are particularly prominent. Furthermore, China faces a severe scarcity of water and soil resources. While China possesses 5% of the world's freshwater resources and 8% of its arable land, it must provide sustenance for 18% of the global population. The continuous increase in grain production has further increased environmental pressure, leading to severe degradation of water and soil resources. Agricultural production urgently needs to shift from pursuing productivity and efficiency to upholding ecological priority. In addition, challenges such as natural disasters and international geopolitical instability pose significant external threats. Therefore, under numerous pressure factors, ensuring food security requires the establishment of a holistic food perspective and takes into account multiple goals including quantity security, nutritional security, capacity security, and ecological security. The development of the bioeconomy promotes the application of biotechnology in agriculture, thereby providing a more effective means of achieving these multifaceted food security objectives (Figure 1).

2.3. Primary Application Scenarios and Objectives of Bioagriculture in China. The application of biotechnology in agriculture drives the progress of crop breeding and expedites the research and usage of biofertilizers, biopesticides, and biofeed. Moreover, the industrial development of bioagriculture can enhance agricultural productivity, ensure the quality of agricultural products, protect and utilize germplasm resources, and promote sustainable agricultural development, thereby contributing to achieving multiple objectives in ensuring China's food security (Figure 1).

2.3.1. Improving Crop Breeding and Agricultural Production Efficiency. Due to complex terrain, environmental factors, climatic conditions, pest and disease challenges, as well as limited breeding efficiency, China's agricultural production remains relatively low efficiency. Research shows that there exists a significant gap between the progress of biological breeding technology and its practical application.[16] China's agricultural production model is predominantly characterized by small-scale farming, resulting in low production efficiency and substantial variations in efficiency among different agricultural entities. Taking maize as an example, agricultural enterprises have the highest efficiency, followed by farmers' professional cooperatives and family farms, with professional large-scale households recording the lowest average production efficiency.[17] Leveraging high-throughput sequencing, from the development of crop genome maps to the identification of high-quality gene resources and the application of molecular marker-assisted breeding, crop breeding efficiency can be enhanced by thousands of times, while breeding cycles can be shortened to two-thirds of their original duration, ultimately enabling the rapid selection of high-quality, environmentally friendly, and nutrient-use-efficient new varieties.[18]

2.3.2. Ensuring the Quality of Agricultural Products. With the development of the economy and society and the improvement of living standards, there is a growing expectation for food safety, quality, and nutritional well-being. However, there are still a series of unresolved issues in the quality and safety of agricultural products in China, such as excessive pesticide residues, soil contamination by heavy metals, abuse of various hormone ripening agents, and challenges in meeting practical regulatory technology needs. Some farmers or businesses, in their pursuit of higher crop yields, illicitly employ excessive fertilizers, persistent pesticides, and misuse drugs containing hormones, resulting in recurrent safety incidents involving agricultural products.[19] In recent years, the development of biotechnology has brought new opportunities for the upgrading and transformation of China's food industry. Synthetic biology technology has enabled the creation of artificial proteins that can reduce the reliance on traditional animal husbandry, thereby alleviating the agricultural burden and driving the evolution of the food industry. At the same time, blockchain technology offers the capability to track and monitor the quality and safety oversight of agricultural products.[20]

2.3.3. Protection and Utilization of Germplasm Resources. Germplasm resources are the cornerstone of the modern seed industry and an important national strategic resource, playing a chip role in modern bioagriculture. China has abundant germplasm resources, housing approximately 450,000 germplasm resources spanning 2300 species within the national crop germplasm conservation system.[21] Nevertheless, when it comes to the protection and utilization of these

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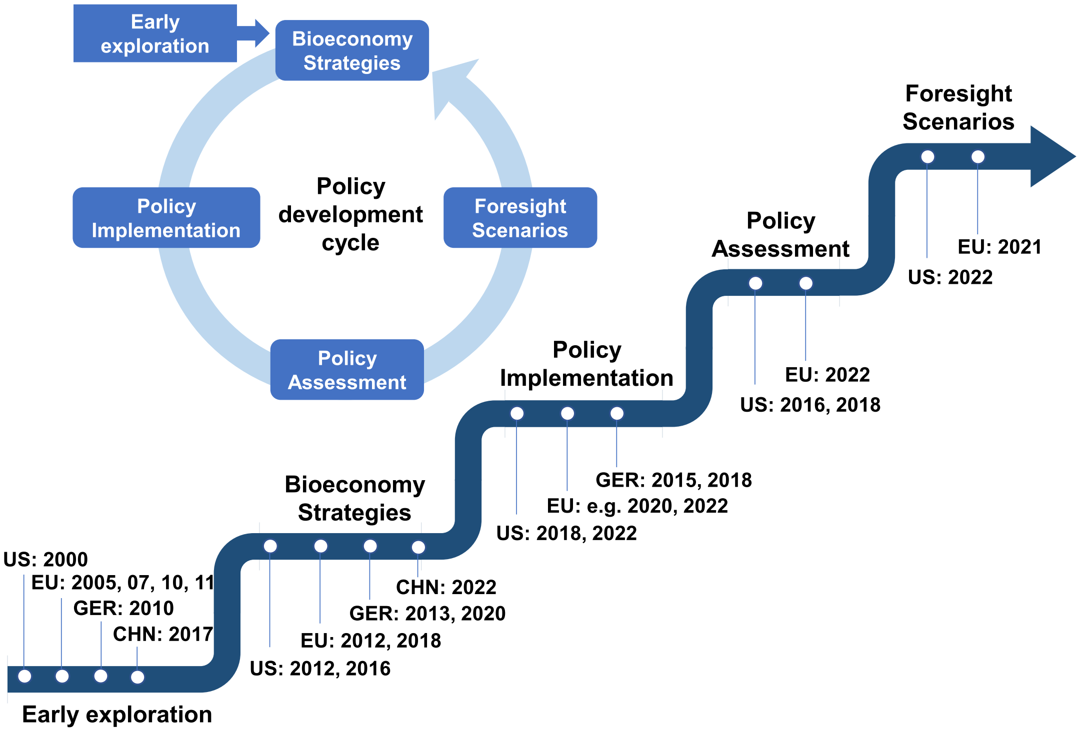

Figure 2. Map of the development of the bioeconomy policies.

germplasm resources, China lags behind developed nations such as the US. Taking wheat as an example, China's utilization rate of germplasm resources for cultivated wheat stands at a mere 10−15%, while by 2018, the US had achieved a utilization rate of 28% for crop germplasm resources.[22] The utilization rate of germplasm resources in China is only approximately half of that in the US, and most new agricultural varieties still remain confined in laboratories and experimental fields, failing to rapidly transition into the industrialization stage and realize profit and income growth akin to developed nations. The advancement of biotechnology, encompassing technologies such as molecular markers, whole genome selection, genome editing, high-throughput sequencing, and SNP chips, is poised to usher in a new era for the safeguarding and utilization of germplasm resources in China.[21] The Plan proposes that China will focus on establishing a germplasm resource protection system with international advanced capabilities, with an emphasis on the national long-term and midterm crop germplasm banks, livestock and poultry gene banks, aquatic germplasm resource banks, and associated resource fields. This system aims to provide high-quality resource materials to support scientific research and breeding endeavors.[23]

2.3.4. Promoting Sustainable Agricultural Development. In September 2020, China pledged to the world at the 75th United Nations General Assembly to strive to reduce greenhouse gas emissions by 55−60% between 2020 and 2030, making China the first major economy to achieve carbon neutrality.[24] In 2018, the greenhouse gas emissions from agricultural activities in China are 830 million tons of carbon dioxide, accounting for 7.42% of the total greenhouse gas emissions.[25] In 2020, agricultural production consumed 86.81 million tons of standard coal, representing 1.8% of China's total coal consumption. Moreover, agricultural pollution caused by excessive pesticide and fertilizer application exacerbates issues like land scarcity, resource scarcity, and environmental pollution. Technological solutions within the bioeconomy, such as biological fertilizers, feed, and pesticides, offer innovative approaches to realize low emissions and sustainable regeneration. Nanobiofertilizers (NBFs), which combine nanoparticles (Si, Zn, Cu, etc.) with biological fertilizers, have emerged as a promising method to promote plant growth, enhance stress resistance, and effectively reduce environmental pollution compared to traditional fertilizers. NBF is now recognized as a more cost-effective and environmentally sustainable agricultural production method.[26] Similarly, biological feeds can play a crucial role in reducing environmental pollution associated with animal husbandry. For instance, feeding fermented feed to cows has been shown to significantly lower the nitrogen and phosphorus content in cow manure while reducing the concentration of harmful gases like H_2S, NH_3, and CO_2 in cowsheds.[27]

3. DEVELOPMENT OF BIOAGRICULTURE IN MAJOR COUNTRIES: LESSONS FOR CHINA

Ensuring food security urgently requires the development of bioeconomy, yet China's bioeconomy is still in its nascent stage. In contrast, bioeconomic development in the US and the EU is relatively mature, with Germany standing out as a rapidly advancing and distinctive nation within the EU regarding bioeconomic growth. Therefore, this section selects the US, the EU, and Germany as representative countries/regions to analyze their policies related to bioeconomy, the development of leading bioeconomy technology, and industries and assesses the impacts of their bioeconomic development. This analysis aims to provide insights for the development of bioagriculture in China.

3.1. Policy Framework and Implementations. A review of bioeconomy policies in various countries reveals a common cycle process in their policy designs. This process typically

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Table 1. List of National Bioeconomy Policies at Different Stages of Policy Development

stages of policy development	countries/regions	strategies	time
early exploration	US	The Biobased Economy of the Twenty-first Century: Agriculture Expanding into Health, Energy, Chemicals, and Materials	2000
		Fostering the Bioeconomic Revolution in Biobased Products and Bioenergy	2000
	EU	New Perspectives on the Knowledge-Based Bio-Economy	2005
		En Route to the Knowledge-Based Bio-Economy (KBBE)	2007
		The Knowledge Based Bio-Economy (KBBE) in Europe: Achievements and Challenges	2010
		The European Bioeconomy in 2030: Delivering Sustainable Growth by Addressing the Grand Societal Challenges	2011
	GER	National Research Strategy BioEconomy 2030: Our Route Toward a Biobased Economy	2010
	CHN	The 13th Five-Year Plan for the Development of the Biological Industry	2017
bioeconomy strategies	US	National Bioeconomy Blueprint	2012
		Strategic Plan for a Thriving and Sustainable Bioeconomy	2016
	EU	Innovating for Sustainable Growth: A Bioeconomy for Europe	2012
		A Sustainable Bioeconomy for Europe: Strengthening the Connection Between Economy, Society and the Environment	2018
	GER	National Bioeconomy Policy Strategy	2013
		National Bioeconomy Strategy	2020
	CHN	The 14th Five-Year Plan for the Development of Bioeconomy	2022
policy implementation	US	The Bioeconomy Initiative: Implementation Framework	2018
		Executive Order on Advancing Biotechnology and Biomanufacturing Innovation for a Sustainable, Safe, and Secure American Bioeconomy	2022
	EU: BG	Strengthening the Role of the Agricultural Sector in the Bioeconomy	2020
		National Strategy for Transition to a Circular Economy	2022
	GER	The High-Tech Strategy 2025 Progress Report	2018
		Bioeconomy in Germany: Opportunities for a Biobased and Sustainable Future	2015
policy assessment	US	Federal Activities Report on the Bioeconomy: ALGAE	2016
		An Economic Impact Analysis of the U.S. Biobased Products Industry	2018
	EU	EU Bioeconomy Strategy Progress Report	2022
foresight scenarios	US	The U.S. Bioeconomy: Charting a Course for a Resilient and Competitive Future	2022
	EU	Future Transitions for the Bioeconomy Toward Sustainable Development and a Climate-Neutral Economy: Foresight Scenarios for the EU Bioeconomy in 2050	2021

includes early exploration, the development of bioeconomy strategies, policy implementation, policy assessment, the creation of foresight scenarios, and subsequent updates to strategic planning (Figure 2 and Table 1). Both the EU and the US have pioneered the development of the bioeconomy and have already completed a full policy formulation cycle. Meanwhile, China's bioeconomy is in its nascent stage, transitioning from strategic planning to policy implementation. Therefore, summarizing the evolution of relevant policies in the EU and the US holds significant implications for guiding and enhancing the development of China's bioeconomy policy.

3.1.1. Early Exploration. Prior to the formulation of their dedicated bioeconomy strategies, various countries have actively engaged in preliminary explorations, crafting relevant policies to discuss concepts, challenges, and objectives related to the bioeconomy. The US took the lead in proposing the development of the bioeconomy and released "The Biobased Economy of the Twenty-first Century: Agriculture Expanding into Health, Energy, Chemicals, and Materials"[28] and "Fostering the Bioeconomic Revolution in Biobased Products and Bioenergy"[29] in 2000. The EU followed immediately and adopted "New Perspectives on the Knowledge-based Bio-economy"[30] in 2005, which, for the first time, defined the bioeconomy as the transformation of life science knowledge into new, sustainable, ecologically efficient, and competitive products. This definition describes a future society that is no longer entirely reliant on fossil fuels for energy and industrial materials. Subsequently, in the years 2007,[8] 2010,[31] 2011,[32] and 2012,[33] relevant policies were introduced to assess the prospects of applying the bioeconomy. What's more, Germany released the "National Research Strategy BioEconomy 2030: Our Route towards a biobased economy"[34] in 2010, committing to creating a sustainable bioeconomy based on natural material cycles. China, on the other hand, initiated its efforts relatively later. Its first comprehensive strategic deployment in the bioindustry was the "13th Five-Year Plan for the Development of the Biological Industry",[35] promulgated by the National Development and Reform Commission (NDRC) in 2017.

3.1.2. Bioeconomy Strategies. Building upon early explorations, countries have successively adopted dedicated bioeconomy strategies. Both the US and the EU adopted a dedicated bioeconomy strategy in 2012[33,36] and updated them in 2016[37] and 2018,[38] respectively. The updated strategy of EU suggests that the bioeconomy covers all sectors and systems that rely on biological resources and recognizes agriculture as one of the most critical primary sectors that use and produce biological resources.[38] After the release of EU's bioeconomy strategy, several EU member states successively adopted their own bioeconomy strategies. By the end of 2022, there are 10 EU member states with dedicated bioeconomy strategies. Among them, Germany adopted "National Bioeconomy Policy Strategy" in 2013[39] and updated it in 2020.[40] In the updated strategy, Germany proposes utilizing the bioeconomy to

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enhance the development of rural areas. China's growing emphasis on the bioeconomy is evident. In May 2022, China formally issued the Plan,[7] marking the country's first five-year plan for the bioeconomy and its inaugural top-level design in this field. The Plan recognizes agriculture as one of its five major application areas. It aims to establish a demonstration and promotion system for bioagriculture, improve the protection, development, and utilization of germplasm resources, and enhance national food security. The Plan also aligns with the objectives of meeting rising consumer demands, supporting sustainable agriculture, and building a comprehensive food safety supervision system to ensure that every bite of food is safe.

3.1.3. Policy Implementation. Based on the released bioeconomy strategies, countries have formulated relevant action plans to promote the implementation of bioeconomy strategies. In 2018, the US released the implementation framework for its bioeconomy strategy.[41] In 2022, the White House of the US issued an executive order on bioeconomy, which emphasizes advancing biotechnology and biomanufacturing innovation for a sustainable, safe, and secure American bioeconomy.[42] Some EU member states opted to integrate the bioeconomy into sector-specific or cross-cutting policies. For example, Bulgaria developed a strategy for "Strengthening the Role of the Agricultural Sector in the Bioeconomy" in 2020.[43] Germany issued "Bioeconomy in Germany: Opportunities for a Bio-based and Sustainable Future" in 2015[44] and "The High-Tech Strategy 2025 Progress Report" in 2018[45] to promote the implementation of the bioeconomy strategy. China has not yet formulated specific national implementation guidelines for the development of bioeconomy. The relatively mature and detailed implementation plans in the US and the EU are of significant reference value for China in formulating and improving its own bioeconomy implementation plan.

3.1.4. Policy Assessment. After a period of implementation of the bioeconomy strategies, countries or regions assess the impacts of the bioeconomy strategies for subsequent adjustments and refinements in the strategic design. For example, in 2018, the US released an assessment report on the economic impact of the U.S. biobased product industry.[46] The European Commission released a progress report on the implementation of the EU 2018 Bioeconomy Strategy by 2022 to assess whether or not the Strategy and/or its action plan requires updating.[43] The report shows that the EU Bioeconomy Strategy is successful and plays an important role in achieving environmental, economic, and social sustainability. It also identified gaps in the current action plan that require further action. Conducting policy assessments can provide guidance for optimizing the policy design. However, due to the later initiation of bioeconomy, systematic policy assessments have not yet been undertaken in China.

3.1.5. Foresight Scenarios. Based on the assessment results of policy implementation, countries formulate or adjust future development pathways for the bioeconomy. Hodgson et al. suggested that the bioeconomy is a new economic model which would use the power of biotechnology, design for bioproduction, and advanced analytics and information technology to create a sustainable and regenerative economic cycle.[9] The bioeconomy has contributed to at least 5.1% of the US GDP over nearly 50 years.[47] Additionally, the projected value of the global bioeconomy is estimated to range between 4 trillion and 30 trillion USD.[9] The EU released a report titled "Future Transitions for the Bioeconomy toward Sustainable Development and a Climate-Neutral Economy: Foresight Scenarios for the EU bioeconomy in 2050". This report provides insights into the future of the bioeconomy in Europe and globally.[48] The report also emphasizes the need for the bioeconomy to focus on implementing a circular, sustainable, and transformative approach. The development goals outlined in the Plan aim to position China's comprehensive capabilities in the bioeconomy among global leaders by 2035. By then, China envisions achieving a new development paradigm characterized by leading technological expertise, robust industrial strength, extensive applications of integration, effective resource assurance, controllable safety risks, and a comprehensive institutional framework.[7]

3.2. Leading Bioeconomy Technology and Industries. The application of the bioeconomy in agriculture is primarily seen in biological breeding, fertilizers, feed, and pesticides:

3.2.1. Biological Breeding. Agricultural biotechnology is increasingly applied to biological breeding, yielding significant results.[49] For instance, genetic modified technology has been employed to develop new crop varieties like corn, soybeans, and cotton with resistance to insects and herbicides.[50−52] The commercial cultivation of these crops has substantially boosted yields, improved quality, reduced pesticide and fertilizer usage, and generated significant environmental benefits, all while ensuring food security.[53−55] Additionally, research efforts have expanded DNA sequencing methods for CRISPR technology, enabling precise editing of animal, plant, and microbial genomes at multiple sites.[51] This innovation aims to enhance existing metabolic pathways and potentially create new ones.[53] The Global Plant Gene Sequencing Program, initiated by the United States National Science Foundation (NSF) in 1996, has made considerable advancements. One notable achievement includes the assembly, annotation, and comparison of 26 distinct maize genomes, which has the potential to increase food and feed crop productivity and develop new plant varieties suitable for resource-scarce marginal lands.[9] Since the commercialization of genetic modified crops in 1996, 29 countries have planted these crops, with 42 countries and regions approving the import of genetic modified varieties. By 2019, these crops covered a total planting area of 190.4 million hectares worldwide. Genetic modified soybeans, maize, and rapeseed have achieved application rates exceeding 90% in strong agricultural nations, such as the US, Brazil, and India, making agricultural biotechnology one of the fastest adopted technologies in practical production. During the 14th Five-Year Plan period, China aims to enhance the research and innovation environment, promote the seamless integration of industry and research, and facilitate efficient allocation of innovation resources. This will be accomplished by prioritizing innovative services and identification platforms for crop molecular breeding, establishing innovation platforms for livestock and poultry breeding, and fostering joint breeding platforms for aquatic products.

3.2.2. Biological Fertilizer. Biofertilizers based on functional microorganisms can significantly extend the effective recycling of nutrients from organic waste, such as livestock manure and crop straw. This approach not only enhances resource utilization but also mitigates environmental pollution. Specifically, biotechnology can be leveraged to screen for exceptional strains capable of efficiently degrading agricultural pollutants, addressing challenges related to continuous cropping in agriculture, and expediting the decomposition of crop straw. Furthermore, these exceptional strains can facilitate the research and development of novel biological fertilizers, including photosynthetic-bacteria-based and lactic-acid-bacteria-based organic fertilizers. In 2020, the global market capacity for biofertilizers reached 1.17 billion dollars, with developed countries such as the US and EU member states accounting for over 20% of biofertilizer usage.[26] Although the number and scale of biofertilizer enterprises in China are experiencing rapid growth, the widespread adoption of biological fertilizers still faces substantial challenges.

3.2.3. Biological Pesticide. The development and promotion of biological pesticides using microbial and plant sources play a vital role in stabilizing crop yields and mitigating agricultural pollution. For example, the utilization of biotechnologies such as genetic engineering, genetic modification, and gene editing for the screening and modification of natural strains can be incorporated into the technical research and production plans of biological pesticide enterprises. Over 30 types of biopesticides have been introduced to the international market.[56] In 2017, the total global sales of biological pesticides reached 3.3 billion dollars, and it is projected to reach a market value of 9.5 billion dollars by 2025, with a compound annual growth rate of 13.9%. Currently, China has developed more than 3000 biological pesticide products.[57] However, biological pesticide enterprises tend to be small in scale and exhibit lower profit margins, resulting in a limited market share for biological pesticides.

3.2.4. Biological Feed. Microbial protein produced through microbial fermentation can be utilized as a biological feed, offering higher nutritional content and greater environmental friendliness. On the one hand, after undergoing fermentation treatment, biological feed can eliminate or reduce various antinutritional factors found in raw feed materials, such as trypsin inhibitors, lectins, antigenic proteins, tannins, phytic acid, alkaloids, and more. This improvement enhances the animals' utilization of feed and their overall growth performance. Besides, in comparison to soybean powder, biological feed boasts higher protein content, lower fat content, favorable amino acid composition, and essential nutrients like glutathione. It also serves as a rich source of vitamins, particularly B-group vitamins, such as thiamine, riboflavin, and folate. On the other hand, biological feed effectively mitigates environmental pollution associated with animal husbandry. For instance, feeding fermented feed to cows significantly reduces nitrogen and phosphorus content in cow manure, as well as lowers the mass concentrations of H_2S, NH_3, and CO_2 in the cowshed. In 2015, the total output value of bioagriculture in China reached 300 billion yuan, with biological feed accounting for 20% of this value. Developed countries have adopted biological feed at rates exceeding 50%, and it is anticipated that the global total output value of biological feed will reach 20 billion dollars by 2025.

3.3. Impact Analysis. Bioeconomy policies help to build a circular and sustainable bioeconomy, which enables people to enjoy a biobased lifestyle, providing them with biobased material (e.g., food, biobased materials, and energy) and nonmaterial (e.g., clean air and water and biodiversity) products and services, thus contributing to positive economic, social, and environmental impacts.

3.3.1. Economic Effects. The development of the bioeconomy can drive the growth of a biotechnology-based circular economy, resulting in significant direct or indirect impacts on the local economy. For instance, Italy's municipal waste-based nutrient valorization strategy for agricultural use generates a total added value of EUR 8.5 million, and 85 jobs can be generated for every 100,000 tons of sewage sludge turned into fertilizer.[58] In Amsterdam, the capital city of The Netherlands, comprehensive recycling of high-value organic bioresidues yields an annual added value of EUR 150 million, generates 1200 new employment opportunities, and simultaneously reduces annual carbon dioxide emissions by 600,000 tonnes.[59] In 2019, the EU's bioeconomy sectors generated EUR 657 billion value added, accounting for 4.7% of its GDP. Among them, agriculture generated an added value of EUR 193 billion, while the manufacture of food, beverage, and tobacco generated an added value of EUR 237 billion, accounting for 29 and 36% of the total added value in the bioeconomy, respectively.[43]

The rapid advancement of biotechnology has spurred the growth of the biobased industries, with agriculture serving as their foundational pillar. Agriculture stands out as one of the primary sources of renewable biomass for the bioeconomy, offering significant potential to enhance both biomass productivity and quantity for the production of high-value biobased products. For example, the total supply of biomass in the EU-27 amounted to 1.066 million tonnes of dry matter in 2017, with approximately 70% originating from agriculture.[43] As of 2017, certain biobased products in the US have exhibited competitiveness surpassing that of petrochemical products in certain sectors, generating annual revenues of at least 125 billion USD, constituting approximately 17–25% of the US fine chemical industry.[60] A sustainable bioeconomy can convert biological waste, residues, and discarded materials to valuable renewable resources. Innovative biotechnology enables the safe conversion of food waste into animal feed, with the anticipation that by 2030, the EU can reduce food waste by 50%, leading to substantial global land savings that could support an additional population of 3 billion people through livestock farming.[61]

The development of the bioeconomy has also propelled the growth of service industries such as scientific research and development, digitalization, and logistics. Cingiz et al. suggested that bioeconomy-related services in the EU generated between EUR 400 and 1000 billion in added value, with growth rates between 2005 and 2015 averaging faster than those of the primary production bioeconomy sectors.[62]

3.3.2. Social Effects. Bioeconomy policies enable a green and socially fair transition by developing sustainable business models and promoting sustainable and social fairness. The development of the bioeconomy can reduce urban–rural disparities and generate new green jobs in emerging circular, biobased food industries and services, adding value to the regional economies. For instance, in Germany, there are 285,000 companies operating in agricultural and forestry sectors, providing employment opportunities for more than 1 million people.[15] The bioeconomy sector employs 773,500 people, which is almost a quarter of Bulgaria's workforce.[43] In 2019, sectors of the bioeconomy employed 17.42 million workers, accounting for 8.3% of the European labor force. Among them, agriculture provided 8.8 million jobs.[43] Furthermore, the European Commission has proposed raising 52.6 billion EUR for addressing societal challenges during the period 2021–2027, with approximately 60% of it directly related to the bioeconomy.[63] This plan primarily funds research and innovation tasks related to major disease prevention and control, innovative drug development, low-

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carbon technology dissemination, and other issues that impact daily life.

3.3.3. Environmental Effects. Innovation and application of biotechnology can lead to the production of environmentally friendly biobased products, reducing the use of chemical fertilizers and pesticides while lowering carbon emissions in agriculture. The application of biotechnologies, such as functional microorganisms and enzyme preparations, in the agricultural and rural sectors promotes achievements in nitrogen and phosphorus removal from water bodies, remediation of heavy-metal-contaminated soils, resource utilization of solid waste, and utilization of bioenergy, thereby advancing the green and sustainable development of agriculture. Biological breeding can yield crop varieties that are adaptable to climate change, salt tolerant, and efficient in nutrient utilization. In addition, compostable tableware and food storage containers made from cassava and potato starch as well as soy-based roof coatings contribute to the reduction of urban carbon emissions. At present, the US annually converts 1 billion tons of biomass into 25% liquid fuels and 50 billion pounds of biobased chemicals, reducing 450 million tons of carbon dioxide emissions, which accounts for nearly 10% of the national emissions.[9] Musonda et al. indicated that by 2050, Germany's biomass potential could save 69 million tons of carbon dioxide equivalent, reducing greenhouse gas emissions by 6% compared to 1990 levels in the energy, construction, transport, and industrial sectors, resulting in a cumulative reduction of 1.72 billion tons of greenhouse gas emissions over the next 30 years.[64]

4. RESULTS AND DISCUSSION

In the new era, China's food security requirements encompass multiple objectives, including quantity security, nutrition security, capacity security, and ecological security. The application of biotechnology in the agricultural sector can provide solutions for food security. Our findings suggest that the US and the EU have relatively mature policies related to the bioeconomy, with the application of biotechnology in agriculture primarily manifested in areas such as biological breeding, biological fertilizer, biological pesticide, and biological feed. Furthermore, the development of the bioeconomy has generated significant economic, social, and environmental benefits. While China's bioeconomy is rapidly developing, the industrial development and policy design for bioagriculture are still in their early stage. Therefore, in China's new era, ensuring food security requires actively promoting the development of bioagriculture.

4.1. Enhancing the Innovative Strength of Bioagricultural Technology. To ensure food security through the development of bioagriculture, China needs to strengthen fundamental research in the biological sciences, with a focus on fostering original innovation as the central driving force behind the enhancement of biotechnology's comprehensive capabilities. In the field of biological breeding, increased investments are essential for conducting research and development of new crop varieties, leveraging biotechnological tools such as genetic engineering and gene editing. Simultaneously, establishing a technology platform for biological breeding resource management and creating a comprehensive germplasm resource database are imperative. These initiatives are instrumental in transitioning China's traditional agriculture into the realm of modern molecular agriculture, often referred to as biological breeding 4.0. Regarding biological pesticides, research and development predominantly rely on microbial and plant sources. The integration of biotechnologies, such as genetic engineering, genetically modified organisms, and gene editing, plays a pivotal role in the screening and modification of natural strains. Furthermore, the resulting biological pesticide products, such as antibiotics, *Beauveria bassiana*, and gibberellin, should be seamlessly integrated into the technology research and production plans of pesticide enterprises. In the context of biological fertilizers, it is crucial to identify exceptional strains capable of efficiently degrading agricultural pollutants, addressing challenges related to continuous cropping in crops, and expediting the decomposition of crop residues. These outstanding strains can be harnessed to create novel biological fertilizers, including photosynthetic bacterial fertilizers and lactic acid bacterial organic fertilizers. Last, within the domain of biological feed, the utilization of microbial fermentation technology is pivotal for developing a highly active yeast-derived biological feed. Alongside this, there should be a concerted effort to vigorously develop new feed additives and enzyme preparations, encompassing compounds such as oligosaccharides, phytases, and composite enzymes.

Furthermore, reducing food losses and expanding food resources beyond cultivated lands are crucial avenues for ensuring food security. It is recommended to enhance support for related biotechnological research and development efforts. For instance, encouraging studies on stable technologies for brown rice, germination techniques, and enzyme technologies can minimize losses and waste in the production and processing of whole grains. Additionally, developing technologies involving algae and other sources can expand food resources into areas such as fisheries and forestry, alleviating the pressure on agriculture to ensure food security.

4.2. Promoting the Transformation of Bioagricultural Science and Technology Achievements. There exists a substantial gap between research efforts and the practical application of China's biological industry. It is imperative to take proactive measures to promote the transformation and utilization of achievements in bioagricultural technology. First, the optimization of the intellectual property protection system is crucial. This system should incentivize technological innovators to invest more resources and effort into the development of bioagricultural technologies while ensuring that they can legally benefit from the transformation of technological achievements. Second, fostering collaboration among enterprises, research institutions, universities, and venture capital organizations is essential. Such collaborations facilitate the swift transition of innovations between academia and industry. Additionally, regional industrial layout adjustments, tailored to distinct regional characteristics, should be implemented. This approach aims to create specialized regional industrial clusters and establish demonstration bases for the innovation and industrialization of bioagriculture. Third, active efforts should be made to provide agricultural technology training and dissemination, such as agricultural extension services, demonstration projects, and training programs. These initiatives are vital in helping farmers and agricultural practitioners understand and adopt new bioagricultural technologies. Fourth, incentive policies, such as tax exemptions, low-interest loans, and subsidy programs, should be developed to encourage farmers and enterprises to embrace new technologies in bioagriculture. Last, the establishment and enhancement of a labeling and certification system for new biotechnology products are essential. This system serves to

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enhance the market credibility and competitiveness of bioagricultural products.

4.3. Gradually Improving the Regulatory System for Biotechnology. Developing an appropriate regulatory framework ensures the safety and sustainability of new bioagricultural technologies and public rights and trust as well. On the one hand, advancing the regulatory system for biotechnology crops and promoting the commercial production and sales of such crops are critical steps. China currently maintains a relatively strict regulatory system for biotechnology crops, such as genetic modified and gene-edited crops, resulting in commercially grown biotechnology crops exhibiting limited varieties, small cultivation areas, and narrow applications. In the future, it becomes imperative to gradually open up the safety approval and commercial planting of biotechnology crops to inject new vitality into China's food security. On the other hand, it is essential to enhance public awareness through scientific dissemination of biotechnology and its related achievements. This involves explaining the potential benefits and risks associated with biotechnological products and guiding the public to have a positive understanding of these products. Public perception and attitudes significantly influence the commercialization of biotechnology crops. Personal and societal values play pivotal roles in decision-making processes regarding the exploration and utilization of specific technologies. Social disputes concerning safety, privacy, ethics, and other issues encompass complex factors related to economics, politics, society, religion, culture, and more within different countries and regions. These complexities necessitate policy guidance. The dissemination of biotechnology and related achievements through government agencies and mainstream media serves as the primary means to enhance the public understanding and acceptance of biotechnology crops.

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Notes

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