Partner Institutions:

Environmental Defense Fund (EDF) Beijing Representative Office

International Food Policy Research Institute (IFPRI)

China Academy for Rural Development (CARD), Zhejiang University

College of Resources and Environmental Sciences, China Agricultural University

Institute of Feed Research of Chinese Academy of Agricultural Sciences (IFR CAAS)

Institute of Geographic Sciences and Natural Resources Research (IGSNRR), Chinese Academy of Sciences (CAS)

Center for Agricultural Resources Research, Institute of Genetics and Developmental Biology (IGDB), Chinese Academy of Sciences

College of Urban and Environmental Sciences, Peking University

Shanghai Academy of Agricultural Sciences (SAAS)

Supporting Institutions:

World Resources Institute (WRI)

Food and Land Use Coalition (FOLU)

Tianren Culture (Hong Kong) Limited

2025 China and Global Food Policy Report

AGFEP

CHINA AND GLOBAL FOOD POLICY REPORT 2025

LOW-CARBON TRANSFORMATION OF CHINESE AGRIFOOD SYSTEMS

Academy of Global Food Economics and Policy AGFEP

AGFEP

Academy of Global Food Economics and Policy, China Agricultural University

The Academy of Global Food Economics and Policy (AGFEP) is a directly affiliated institute of China Agricultural University. The institute is headed by Dr. Shenggen Fan, Chair Professor at China Agricultural University and former Director General of the International Food Policy Research Institute (IFPRI). The members of AGFEP include faculty members and researchers from China Agricultural University, Zhejiang University, Beijing University and AgroScope, Switzerland. The academic committee of AGFEP is composed of 14 scholars from both domestic and international communities, specializing in food policy, environmental science, nutrition, and agricultural economics.

AGFEP features a close integration of the global agenda and China's practices, a multidisciplinary research approach, and a management mechanism emphasizing collaboration and talent development. AGFEP focuses on food systems transformation and aims to share China's experience and lessons with the world. The key research areas include reshaping global and Chinese food systems, analyzing responses to unexpected public emergencies, and exploring the food-economy-environment-health nexus. The academy provides forward-looking and evidence-based strategic policy options for China as well as the global community.

2021 China and Global Food Policy Report: Rethinking Agrifood Systems for the Post-COVID World

2022 China and Global Food Policy Report: Reforming Agricultural Support Policy for Transforming Agrifood Systems

2023China and Global Food Policy Report: Promoting Sustainable Healthy Diets for Transforming Agrifood Systems

2024 China and Global Food Policy Report: Building a Sustainable and Diversified Food Supply to Foster Agrifood Systems Transformation

Scan QR code for annual reports

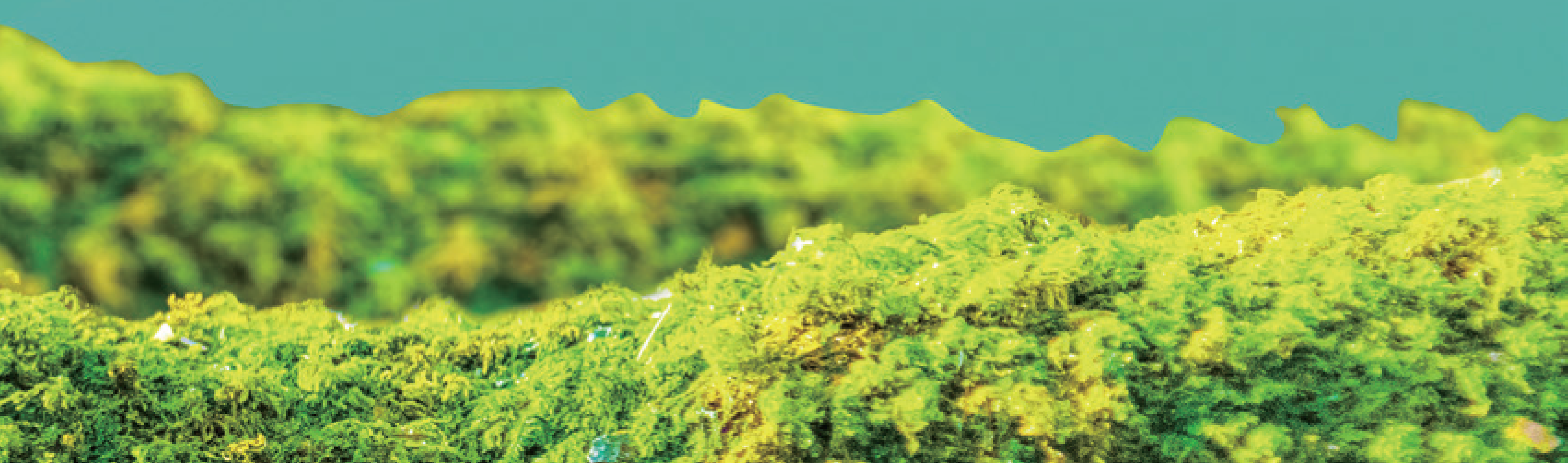
Contents

AGFEP

AGFEP

CHINA
AND GLOBAL
FOOD POLICY
REPORT
2025

LOW-CARBON TRANSFORMATION OF CHINESE AGRIFOOD SYSTEMS



Foreword I

The Chinese government has set forth the goal of achieving modernization by 2035. Among the core objectives are the "widespread adoption of green production and lifestyles, a steady decline in carbon emissions after peaking, significant improvements in ecological environment, and the foundational realization of the Beautiful China Vision".

The Third Plenary Session of the 20th Central Committee further emphasized that by 2035, China should basically achieve modernization of its national governance system and capacity. Central to this objective is "the construction of a Beautiful China, which involves accelerating the comprehensive green transformation of economic and social development, improving ecological and environmental governance, promoting ecology-first, conservation-intensive, green and low-carbon development, and fostering harmony between humans and nature. The "Three Rural Issues", agriculture, rural areas, and farmers, are of paramount importance in building a modern socialist country. They represent a critical weakness in China's modernization process. Advancing agricultural and rural modernization is both a a pressing task of the era and a profound historical responsibility. Rural areas play a vital role in ensuring agricultural product supply and national food security, preserving the ecological environment, and safeguarding China's rich cultural heritage. Environmental protection and ecological security are challenges rooted more in rural than urban settings.

For many years, excessive pressure on natural resources and environment has caused severe degradation. Farmland is suffering: acidification in the south, salinization in the north, and black soil degradation in the northeast. Although China has made significant progress in reducing the use of fertilizers and pesticides, ecological restoration is a long-term effort. Internationally, global climate change, amidst unprecedented transformation not seen in a century, is impacting food supplies and prices, reshaping international relations. China must remain vigilant in addressing climate change and securing national food security. Rural areas are the frontlines of ecological civilization. We must firmly embrace the principle that lucid waters and lush mountains are invaluable assets, and promote a sound ecological mindset, responsible consumption patterns, and a moral outlook aligned with green development. It is imperative to deepen efforts in building rural ecological civilization, steadily reduce agricultural emissions, promote carbon sequestration practices such as no-till and reduced-till farming, enhance the utilization of livestock waste, and advance research on agricultural mitigation technologies. Accelerating green and low-carbon agricultural development and cultivating sustainable production and consumption patterns will be essential in building a green, circular, and low-carbon agricultural powerhouse that supports China's carbon peaking and neutrality targets.

Against this backdrop, the upcoming 2025 China and Global Food Policy Report themed "Low-carbon Transformation of Agrifood Systems while Ensuring Food and Nutrition Security" is both timely and forward-looking. Drawing on robust data and modelling, the report provides a comprehensive analysis of China's progress and challenges in low-carbon transformation of its agrifood system. It highlights key sectors, such as rice production, livestock, energy transition, and food loss and waste reduction, while integrating interdisciplinary insights, international perspectives, and Chinese characteristics. The report offters valuable guidance to policymakers, researchers, and industry stakeholders, advancing China's agri-supporting supporting national climate goals, and contributing Chinese solutions to global efforts in combating climate change.

Xiwen Chen
The 13th National People's Congress Chairman of the
Agriculture and Rural Affairs Committee Member

Foreword II

In recent years, global climate change has posed severe challenges to economic development, food and nutrition security, public health, and even human survival. Addressing climate change has become a common responsibility of the international community. In this context, promoting the sustainable transformation of agrifood systems holds critical strategic importance. Globally, agrifood systems are among the major sources of greenhouse gas (GHG) emissions. According to the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report, agrifood systems contribute approximately 23% to 42% of total global GHG emissions. With a growing global population and rising demand for food, GHG emissions from this sector could rise by 60% to 90% by 2050 if current trends persist, posing a formidable challenge to global climate governance.

China has long been an active participant and key contributor to global climate governance under the framework of the Paris Agreement. In 2020, the Chinese government made a landmark international pledge to peak carbon emissions before 2030 and achieve carbon neutrality before 2060, demonstrating its strong commitment to global climate action. In October 2024, the World Agrifood Innovation Conference was successfully held in Pinggu, Beijing, under the theme "Climate Change and Agrifood Systems Transformation." Co-hosted by China Agricultural University (CAU) and other institutions, the conference brought together nearly 800 agrifood leaders, experts, scholars, and young professionals from 76 countries and regions. Participants engaged in in-depth dialogue on key topics and jointly explored ideas and solutions for addressing climate challenges through the transformation of agrifood systems.

Against this backdrop, the Academy of Global Food Economics and Policy at CAU, led by Chair Professor Shenggen Fan, partnered with a number of domestic and international collaborators to conduct in-depth research and released the 2025 China and Global Food Policy Report. This marks the fifth consecutive year that the Academy has published a flagship report focused on the transformation of agrifood systems. The 2025 report is themed "Low-carbon Transformation of Agrifood Systems." Drawing on China's practical experiences, empirical evidence, and interdisciplinary integrated modeling, the report investigates emission reduction across key areas such as rice production, livestock, energy transition, and food loss and waste. It explores viable pathways and policy options for advancing the low-carbon transformation of China's agrifood systems. The report highlights significant progress China has made in reducing GHG emissions from rice cultivation and livestock production, promoting clean energy transition, and curbing food loss and waste. It also underscores the importance of fostering greater public awareness, formulating national strategies and action plans, strengthening policy support frameworks, accelerating R&D and deployment of efficient, green, and low-carbon technologies, innovations in agrifood governance to encourage broad stakeholder participation, and enhance international cooperation.

In recent years, CAU has actively its mission aligned with national strategies by strengthening interdisciplinary programs on green and low-carbon agriculture, cultivating cross-disciplinary innovation talent, and promoting collaborative research. In the future, CAU remains committed to its mission as a leading national agricultural institution. The university will continue to pursue breakthroughs in core green and low-carbon technologies, advance cutting-edge research, and reform talent development systems. By leveraging the synergistic power of science and technology, academic innovation, and human capital, CAU is dedicated to contributing to major national goals such as food security, sustainable agricultural development, and rural revitalization, playing an integral role in building a strong, modern agricultural nation.

Qixin Sun
President of China Agricultural University

Foreword III

Climate change is one of the most pressing global challenges of our time, and transforming agriculture and food systems (hereafter referred to as "agrifood systems") plays a crucial role in addressing this crisis. Encompassing the entire value chain from agricultural input production, farming activities, and land-use changes to food processing, transportation, consumption, and waste management, agrifood systems are responsible for approximately one-third of global greenhouse gas emissions, making them a major contributor to climate change. Achieving low-carbon transitions in agrifood systems is not only a core pillar for fulfilling the Paris Agreement and the United Nations Sustainable Development Goals (SDGs), but also represents a strategic focus in global climate governance. Despite proactive global efforts to advance low-carbon transformations, progress has been constrained by inadequate international commitments, technological dissemination barriers, and funding shortfalls. China's transition to low-carbon agrifood systems carries profound global significance. With the challenge of feeding a large population on limited natural resources, China faces three major priorities in agrifood system transformation: food security, nutritional health, and climate change mitigation. In recent years, the country has made notable progress in reducing agricultural emissions, particularly in rice cultivation, livestock management, energy structure optimization, and reducing food loss and waste. However, the pressures from rising food demand and evolving dietary patterns continue to strain emission reduction efforts. This underscores the urgent need to enhance synergies between emission reduction, resource efficiency, and sustainable resource utilization. These factors are vital to safeguarding China's food security, public health, and long-term development, shaping the strategic objectives, directions, and policy priorities of agrifood system transformation in the new era.

Led by Professor Shenggen Fan of China Agricultural University, the Academy of Global Food Economics and Policy, in collaboration with leading domestic and international research institutions, jointly releases the 2025 *China and Global Food Policy Report*. Employing a systemic perspective, the report examines the progress and challenges of low-carbon transitions in agrifood systems both globally and within China, offering in-depth analyses of key emission reduction pathways and outcomes in priority sectors such as rice cultivation, livestock management, energy transformation, and food loss and waste. It emphasizes the crucial role of technological innovation, policy optimization (such as carbon market development and food loss and waste reduction legislation), and multi-stakeholder collaboration. Furthermore, the report recommends enhancing climate finance, refining carbon accounting systems, and accelerating the dissemination of low-carbon technologies, thereby providing actionable guidance for achieving high-quality, low-carbon transformations of agrifood systems.

We believe this report will serve as a valuable reference for policymakers, academia, and industry, driving agrifood systems toward greater efficiency, lower carbon emissions, health and nutrition, sustainability, and inclusiveness. Ultimately, it aims to build a greener, and more resilient future for China and the world.

Keming Qian
Chief Research Fellow at the Chinese Academy of Agricultural Sciences
Former Vice Minister of Commerce

Foreword IV

Climate change is affecting the sustainable development of human society at an unprecedented speed and scale. The increasing frequency of extreme weather events, the degradation of ecosystems, and the disruption of food supply chains have become common global challenges. In response, the report of the 20th National Congress of the Communist Party of China explicitly called for the "broad establishment of eco-friendly ways of work and life" and the "acceleration of the transition to a model of green development," which is a strategic initiative essential for propelling China into a new stage of high-quality development.

Agriculture is both a significant source of greenhouse gas emissions and a key sector for achieving carbon peaking and carbon neutrality. Accelerating the low-carbon transformation of the agrifood system is not only an urgent response to global climate change, but also an important measure for ensuring national food security and safety, improving population nutrition and health, and to advancing the construction of an ecological civilization. In recent years, China has made remarkable strides in promoting green agricultural development. There have been measurable achievements in pollution reduction and carbon mitigation. The use of chemical fertilizers and pesticides has continued to decline, water-saving irrigation technologies have been widely adopted, the resource utilization rate of for livestock and poultry manure has steadily improved, and agricultural production is gradually transitioning toward greater efficiency, environmental friendliness, and lower carbon emissions.

However, we must also clearly acknowledge that shifting dietary patterns and consumption upgrades among residents are driving continuously growing food demand, placing increasing pressure on natural resources and the environment. Agriculture continues to grapple with the dual challenges of reducing emissions while increasing efficiency, underscoring an urgent need to strengthen theoretical research and develop more effective policy support.

In this context, the 2025 China and Global Food Policy Report presents a timely and valuable contribution. Spearheaded by Professor Fan Shenggen of China Agricultural University's Academy of Global Food Economics and Policy, in collaboration with leading domestic and international institutions, the report adopts the theme ""Low-carbon Transformation of Agrifood Systems". Deeply grounded in China's national context yet possessing a global perspective, it leverages interdisciplinary approaches to analyze emission-reduction pathways in key areas, such as rice production, animal husbandry, agricultural energy, and food loss and waste. This report synthesizes key takeaways from China's practical experience in agricultural low-carbon transformation and advances comprehensive policy recommendations encompassing technological innovation, institutional framework, market mechanisms, and international cooperation. Collectively, these findings offer an empirical roadmap and strategic reference point for advancing green and low-carbon agricultural development.

Having long been involved in agricultural policy research and management practices, I am profoundly aware that agricultural green development is non-negotiable, it is an essential, long-term strategic imperative. Currently, China stands at a critical juncture, accelerating the transition from traditional to modern agriculture. We must:

1. Uphold development principles prioritizing ecology, conservation, intensification, and green low-carbon practices.

2. Integrate agricultural emission reduction and carbon sequestration comprehensively into rural revitalization and agricultural/rural modernization plans.

3. Holistically balance among food security, farmer income, industrial development, ecological protection, and climate response.

4. Foster a new paradigm of green, low-carbon development characterized by multi-stakeholder, multi-level, and systematically integrated synergy.

I trust the release of this report will further consolidate consensus, inspire innovations, and galvanize actions, cultivating broad societal support for agricultural low-carbon transformation and green development. It contributes vital insights and momentum towards building a strong agricultural nation and realizing a Chinese-style modernization grounded in harmony between humanity and nature.

It is noteworthy that this year's China and Global Food Policy Report marks the fifth consecutive annual edition spearheaded by Professor Fan Shenggen's Academy of Global Food Economics and Policy (China Agricultural University). I have had the privilege of engaging with this series and witnessing its significant impact. These reports uniquely blend Chinese realities with a global perspective, employing interdisciplinary approaches from agricultural economics, environmental science, nutrition, and public policy. Over time, they have established robust, canonical frameworks for analyzing agrifood system transformation and become essential tools for policy simulation.

Directly addressing national strategic priorities, the reports have proven invaluable, in terms of supporting the "Healthy China" and "Dual Carbon" goals; fostering alignment between agriculture/food supply and nutrition; enhancing policy coherence between trade and health; and guiding shifts in social and consumer behavior. They serve as a scientific bedrock for China's agrifood system policymaking; actionable blueprints for global sustainable development; and influential reference literature in domestic and international agricultural economics, advancing agri-food system theory while exemplifying deep integration of academic rigor with practical needs.

Mengshan Chen

Chairman of the Fourth National Food and Nutrition Advisory Committee

Former Party Secretary of the Chinese Academy of Agricultural Sciences

Main Findings and Policy Recommendations

Strategic Pathways for the Low-carbon Transformation of China's Agrifood Systems

Shenggen Fan[1,2], Ji Gao[3], Wei Si[1,2], and Ting Meng[1,2]

1. Academy of Global Food Economics and Policy, China Agricultural University
2. College of Economics and Management, China Agricultural University
3. Environmental Defense Fund (EDF) Beijing Representative Office

Agrifood systems are fundamental to global food and nutrition security but are increasingly vulnerable to climate change. At the same time, they are a significant contributor to greenhouse gas (GHG) emissions, making them a critical sector for climate action. GHG emissions from the agrifood systems reached 16.24 billion tonnes of carbon dioxide equivalent (CO_2eq) in 2022, 30.3% of global emissions. Meanwhile, optimizing carbon sequestration in agricultural land use offers a pathway towards net-zero emissions in agriculture, forestry, and other land uses by 2050. Thus, agrifood systems are both a major emitter and a potential carbon sink, placing them at the center of climate strategies.

The international consensus on transforming agrifood systems towards low-carbon and resilient mode is growing. The 28th Conference of the Parties (COP28) in 2023 marked a turning point by formally integrating agrifood systems transformation into the United Nations Framework Convention on Climate Change (UNFCCC) agenda for the first time, advocating systemic, cross-sectoral, and multi-stakeholder reforms. The United Arab Emirates (UAE) Declaration on Resilient Food Systems, Sustainable Agriculture and Climate Action, endorsed by 161 countries and regions including China, the United States, the European Union, and Brazil, emphasized agrifood systems transformation as a key route to achieving the temperature control targets of the Paris Agreement, backed by an action plan with measurable indicators.

China's low-carbon agrifood transformation holds global significance, aligning with its domestic "Dual Carbon" goals of carbon peaking and carbon neutrality, while contributing to global emission reductions. The Chinese government has established a robust policy framework through its "Action Plan for Carbon Peaking Before 2030" and a range of sectoral strategies. The Ministry of Agriculture and Rural Affairs and the National Development and Reform Commission, jointly launched the "Implementation Plan for Emission Reduction and Carbon Sequestration in Agriculture and Rural Areas," demonstrating a government-led approach with sectoral breakthroughs. These policies not only surpass China's nationally determined contributions (NDCs) but also provide replicable models through the South-South Climate Cooperation.

While China's agrifood systems must be transformed to address climate crisis while must always place food and nutrition security as the top priority. This transformation spans all segments of the supply chain and must reconcile diverse development goals while minimizing trade-offs. This report adopts "low-carbon transformation" as its guiding principle and "systems thinking" as its methodological framework. It examines transformations in crop and livestock production, energy optimization, food loss and waste management, and their synergistic integration. It proposes actionable pathways through technological innovation, institutional reform, and international cooperation.

As part of the "China and Global Food Policy Report" series (2021-2024), the 2025 report builds on prior explorations of repositioning agrifood support policies sustainable diets, and diversified food supply systems under the "Big Food Concept". The 2025 report conducts a systematic estimation of China's agrifood systems' carbon emissions and sources, and offers targeted low-carbon pathways using interdisciplinary methods, quantitative analysis, and policy scenario modeling. The report integrates international best practices with China's context to provide systematic, evidence-based, and forward-looking policy guidance for policymakers, researchers, and industry stakeholders.

This report was jointly produced by the Academy of Global Food Economics and Policy (AGFEP) of China Agricultural University and several key institutions, including Environmental Defense Fund, the International Food Policy Research Institute (IFPRI), the China Academy of Rural Development at Zhejiang University, the College of Resources and Environmental Sciences at China Agricultural University, the Feed Research Institute of the Chinese Academy of Agricultural Sciences, the Institute of Geographic Sciences and Natural Resources Research of the Chinese Academy of Sciences, the Center for Agricultural Resources Research of the Institute of Genetics and Developmental Biology of the Chinese Academy of Sciences, the College of Urban and Environmental Sciences at Beijing University, and the Shanghai Academy of Agricultural Sciences.

The chapter arrangement and research content of the report are as follows: Chapter 1 reviews global and Chinese progress and challenges in agrifood systems' low-carbon transformation, proposing actionable strategies and policies. Chapter 2 evaluates methane emissions in rice cultivation and proposes region-specific low-carbon cultivation models. Chapter 3 assesses carbon emissions of the China's livestock sector, analyzes domestic and international reduction practices, estimates technological potential for China, and offers policy recommendations. Chapter 4 investigates energy consumption and emissions across the agrifood value chain, exploring clean energy and efficiency-based transition pathways. Chapter 5 quantifies food loss and waste, explores emission reduction scenarios, and offers governance recommendations. Based on the analysis of the previous chapters, Chapter 6 identifies sources of greenhouse gas emissions and various carbon sinks in China's agrifood systems, summarizes various emission reduction measures and carbon sequestration pathways, and evaluates the effectiveness of different mitigation strategies through a multi-proned approach.

Key Findings

1. Global Progress: The transformation of agrifood systems has received increasing global attention. Significant international progress has been made in reducing crop and livestock emissions, and promoting low-carbon energy transitions, as well as reducing food loss and waste, transforming dietary structures, and optimizing agriculture, forestry, and other land use. However, China faces dual constraints of low public awareness and weak strategic planning, coupled with low policy support and inadequate R&D investment on low-carbon technologies.

2. Rice Methane Emissions: China's rice methane emissions exhibit significant regional variation. Methane emission intensity is influenced by the interactive effects of multiple factors, including soil, water, climate, and management practices. Double-cropping areas in the south have higher emission intensity due to prolonged flooding, while northeastern regions emit less due to cooler climate. Water management, fertilization, and seed innovations demonstrate high synergistic mitigation potential.

3. Livestock Sector Emissions: The livestock sector accounts for a major share of Chinese agrifood emissions, dominated by enteric fermentation and manure management. Emission shares are 49% from cattle, 23% from pigs, 13% from sheep, and 15% from other livestock. Carbon emissions from enteric fermentation exceed those from manure management, while carbon emissions from energy consumption account for a relatively small proportion. Mitigation strategies include low-emission breeds, clean energy adoption, pasture management, and dietary shifts from red meat to white meat.

4. Energy Structure and Transition: Since 2015, agrifood energy-related emissions have been around 630 million tonnes of CO_2eq. Electricity has gradually displaced coal in the energy mix. Tailored transition strategies are needed across pre-production, production, and post-production stages.

5. Food Loss and Waste: Food loss and waste contribute 4% of China's total emissions, concentrated in post-harvest handling (41.6%), production (22.7%), and consumption (19.6%) stages. Fruits and vegetables are the most wasted. A 50% reduction in consumption-end waste could result in a 31% reduction in related emissions.

6. Future Emission Trajectories: Without interventions, agrifood systems carbon emissions could exceed 1.8 billion tonnes of CO_2eq by 2060. Multiple coordinated measures, including productivity improvement, low-carbon technology development and application, reducing food losses and waste, adjusting food consumption structure, and low-carbon energy transition and upgrading, could reduce emissions by over 60%, to around 650 million tonnes of CO_2eq.

7. Carbon Sink Potential: In 2021, China's LULUCF (Land Use, Land Use Change and Forestry) carbon sinks reached 1.32 billion tonnes, with potential to reach 1.76 billion tonnes by 2060. This could offset all agrifood emissions and provide a net of 1.1 billion tonnes of surplus towards national carbon neutrality goal.

Policy Recommendations

First, the agrifood systems have enormous potential for emission reduction, and this reduction needs to be accelerated through improving awareness, policy, technology, and institutional innovation. It calls to enhance understanding of the low-carbon transformation in agrifood systems and develop national strategies and action plans. Policy support systems need to be established to promote the low-carbon transformation of agrifood systems, aiming to accelerate the research, development, and promotion of efficient, green, low-carbon, and multi-beneficial technologies. Additionally, it is crucial to encourage business model innovation, stimulate multi-stakeholder participation, and strengthen international cooperation, to share best practices and foster a global approach to the low-carbon transformation of agrifood systems.

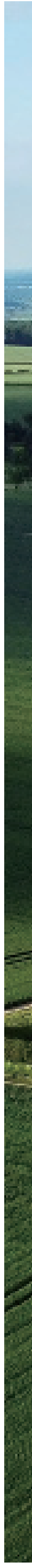
Second, reducing methane emissions in crop production, especially in rice, requires the integration of artificial intelligence technology, modern breeding innovations, and institutional reforms. Facilitating the integrated "AI + agriculture" applications can reduce labor costs and improve water management and fertilization efficiency through intelligent sensing and precision control. Increasing breeding investment in low-emission, nutrition-synergistic varieties can achieve multi-objective coordination of yield, nutrition, and emission reduction. The emission reduction can be further improved by enhancing land transfer and incentive mechanisms, promoting the aggregation of small-scale farmers into large-scale operations, increasing the adoption rates of emission reduction technologies, and constructing promotable and sustainable emission reduction systems.

Third, the low-carbon transition in the livestock industry requires improvements in carbon emission monitoring, the development of green and low-carbon technologies, and promotion of a balanced diet and crop-livestock integration. Policies are needed to enhance the development of carbon emission monitoring and accounting systems, accelerate research and development in livestock breeding, novel feed additives, clean energy, and alternative proteins, as well as promote the integration of intelligent and information technology. Additionally, crop-livestock cycling and ecological livestock farming can help create low-carbon product brands and drive the structural upgrading of the livestock industry through demand-driven transformation. Policy support, carbon markets, and technology innovation can help guide the low-carbon development of the livestock industry.

Fourth, stimulating energy transformation in agrifood systems requires a series of targeted measures. The energy transformation requires cross-departmental collaboration to integrate and innovate policy tools; advance the research, development, and promotion of key technologies; construct an energy transformation information platform with supporting data systems; improve and innovate emission reduction incentive mechanisms; strengthen bidirectional international technical cooperation; and actively participate in the formulation and revision of international rules.

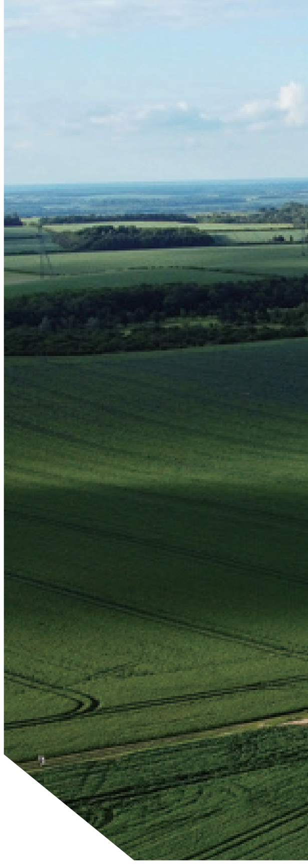
Fifth, to reduce food loss and waste, three primary directions need to be focused on: chain coordination, behavioral transformation, and institutional guarantee to promote systematic, low-carbon, and rule-of-law governance processes. It calls for strengthening supply chain coordination, enhancing cold chain facilities and digital systems, and promoting integrated loss and carbon reduction strategies. Policy incentives and public education must be implemented to guide the transformation of consumption behavior and cultivate a culture of grain conservation. Key instruments include enhancing policy and legal systems, promoting cross-departmental coordination and local legislation, and expanding governance effectiveness through international cooperation.

Sixth, it is crucial to formulate low-carbon transformation plans for agrifood systems, implement multiple measures to promote emission reduction, and pursue the coordinated development of carbon sequestration through various approaches. Carbon emissions from all segments need to be incorporated into a unified framework to establish accounting and monitoring systems and clarify tasks by stages. New technologies should be leveraged to achieve production increase and emission reduction. Research and development (R&D) can stimulate green, low-carbon, and production-increasing synergistic technologies to enhance agricultural productivity and reduce costs. To increase carbon sinks from agrifood, land use and forests, multiple measures need to be adopted, including afforestation, conservation tillage, and grassland ecological restoration.



Chapter 1

Progress and Gaps in the Low-carbon Transformation of Global and China's Agrifood Systems



Xiaolong Feng[1,2], Xuezhen Xu[1,2], and Shenggen Fan[1,2]

1. Academy of Global Food Economics and Policy, China Agricultural University
2. College of Economics and Management, China Agricultural University

Key Findings

● The low-carbon transformation of agrifood systems holds critical significance for achieving the goals of the *Paris Agreement* and is accelerating globally. This transformation has been elevated to the forefront of the global policy agenda through the United Nations Food Systems Summit. Concurrently, the Food and Agriculture Organization has launched multiple strategic initiatives to promote and operationalize low-carbon actions across agrifood systems. The Conference of the Parties to the United Nations Framework Convention on Climate Change (cop28) has formally integrated greenhouse gas (GHG) emissions reduction in agrifood systems into the global climate action framework, issuing its first dedicated declaration on agrifood systems and climate change. Meanwhile, the World Bank continues to scale up climate financing for transforming agrifood systems.

● Significant global progress has been achieved across multiple dimensions. In rice cultivation, notable advances include improved water management, innovative cultivation models, soil amendment technologies, and the breeding of low-emission rice varieties. The livestock sector has accelerated the development of emission governance frameworks, reinforced by strengthened national climate commitments and enhanced technical practices. Renewable energy adoption is expanding across agrifood supply chains, supported by targeted policies. Simultaneously, efforts to reduce food loss and waste are underway, while sustainable and healthy diets are becoming more accepted. Tangible progress has been made in promoting climate-friendly dietary patterns and advancing alternative protein technologies. Ecosystem management has improved through forest carbon sequestration, sustainable soil practices, and the development of marine and grassland carbon sinks, with pioneering carbon market mechanisms emerging in several developed economies. Despite these advancements, the global transition continues to face key challenges, including insufficient international commitments, slow implementation progress, inadequate financing, and limited technological innovation and diffusion.

● China has institutionalized low-carbon commitments within its national agricultural modernization strategy, incorporating specific mitigation and carbon sink enhancement measures into its Nationally

Determined Contributions (NDCs). Notable progress includes significant emission reductions in rice and livestock production through innovative policies and technologies. The transformation of agricultural energy systems is accelerating via renewable energy deployment, biomass utilization, and energy-saving project implementation. National legislative and policy mechanisms have contributed to substantial reductions in post-harvest losses and consumer food waste. A policy framework for health diet has been established, underpinned by the issuance of national dietary guidelines. Carbon sequestration capacity has been enhanced through integrated cropland management, forestry conservation, and grassland restoration. Nevertheless, China still faces major constraints, including low public awareness, gaps in strategic planning, underdeveloped methodological support systems, insufficient policy incentives, and inadequate scaling of low-carbon technologies.

Policy Recommendations

● First, the transformation of agrifood systems must be recognized as a systemic undertaking requiring greater public awareness of its mitigation potential. It demands the formulation of national strategies and action plans, supported by operational models that combine government leadership with multi-stakeholder collaboration. Concurrently, strengthening monitoring, reporting, and verification systems for GHG emissions from the agrifood systems and establishing a robust set of indicators to track transformation progress of agrifood systems are imperative.

● Second, low-carbon policy must extend across the entire agrifood value chain. This entails developing an integrated policy support framework through diversifying policy instruments, optimizing support structures, enhancing infrastructure investment, adjusting policy priorities, and advancing eco-carbon market mechanisms.

● Third, scaling up R&D investments in green mitigation and sequestration technologies should be a top government priority, particularly in reducing GHG emissions from rice and livestock production, and enhancing cropland soil carbon storage. Innovation in AI-powered agricultural technologies and climate-smart production models should be accelerated. To ensure these technologies are widely adopted, effective dissemination mechanisms and incentives must be established, empowering producers to contribute meaningfully to GHG emission reduction and enhanced carbon sequestration capacity.

● Fourth, the pivotal roles of enterprises, socialized service systems, and emerging agricultural entities must be fully leveraged. Actively involving both consumers and businesses in mitigation efforts should be encouraged to achieving transformative impact across the system.

● Fifth, international best practices in GHG emission reduction across agrifood systems should be systematically studied. Developing cooperative strategies for green, low-carbon supply chains with trading partners, sharing China's transformation experience, and strengthening international collaboration are important steps to accelerate global decarbonization in the agrifood sector.

1.1 Progress and Challenges in the Low-Carbon Transformation of Global Agrifood systems

1.1.1 Process of Low-carbon Transformation in Global Agrifood Systems

Agrifood systems are a key sector for both mitigating and adapting to climate change (Rosenzweig et al., 2020; Rosenzweig et al., 2021; Costa et al., 2022). Since the adoption of the *Paris Agreement* in 2015, the low-carbon transformation of agrifood systems has garnered widespread attention from the international community (Amahnui et al., 2025). Their role in Nationally Determined Contributions (NDCs) has become increasingly prominent. As a core compliance mechanism of the *Paris Agreement*, nearly all Parties have identified agrifood systems as a priority area for climate change adaptation (94%) and mitigation (91%) in their NDCs (Crumpler et al., 2024), highlighting the sector's enormous potential as a climate change solution.

Agrifood systems are a significant source of greenhouse gas (GHG) emissions, encompassing a series of interconnected activities. These include agricultural input manufacturing, agricultural production, land use change, supply chain processes (e.g., food processing, packaging, transportation, and retail), household consumption, and food system waste management (Karl et al., 2024; Amahnui et al., 2025). Studies estimate that one-third of global GHG emissions originate from agrifood systems (Crippa et al., 2021; Costa et al., 2022). Among these, agricultural production is the largest emission source, contributing 39% of total emissions, followed by land use and land-use change (32%) and supply chain activities (29%) (Crippa et al., 2021). Additional food loss and waste generated 9.3 billion tonnes of CO_2eq in 2017, accounting for approximately half of the sector's total GHG emissions (Zhu et al., 2023).

According to the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report, GHG emissions from global agrifood systems increased from 14 billion tonnes of CO_2eq per year in 1990 to 17 billion tonnes in 2018, a 21.4% increase (Babiker et al., 2022). Projections suggest that these emissions will continue rising due to population growth and increasing food demands, with estimates indicating an increase of 60%-90% by 2050 (Riahi et al., 2017; Springmann et al., 2018; Mbow et al., 2019). If the current emission trends persist, they may hinder global climate goals, even if fossil fuel emissions were to cease immediately. Such trajectories could undermine the achievement of the 1.5°C and 2°C temperature targets set in the *Paris Agreement* (Clark et al., 2020). Therefore, a low-carbon transformation of agrifood systems is both imperative and pivotal for the timely realization of these climate targets.

At the global level, the transformation of agrifood systems has become an increasingly urgent priority. The United Nations (UN) has taken a leading role in promoting this agenda. Agrifood systems are central to achieving the UN's 17 Sustainable Development Goals (SDGs) and constitute a core pillar of the global sustainable development agenda (Fan et al., 2022). The UN Food Systems Summit, held on September 23, 2021 in New York, elevated food systems to the top of the global policy agenda (IFPRI, 2022)[1]. The summit's goals included developing concrete actions and measurable progress frameworks, enhancing global awareness, establishing guiding principles, and creating mechanisms for follow-up and review[2]. It also identified five Action Tracks to guide the transformation. Subsequently, the UN established the Food Systems Coordination Hub to drive global efforts. At the 2023 UN Food Systems Summit Stocktaking Moment in Rome (July 24 to July 26, 2023), over 2,000 representatives from approximately 180 countries and regions gathered, with more than 100 countries voluntarily submitted progress reports on their agrifood systems transformation.

FAO is also actively promoting global low-carbon transformation actions in agrifood systems. In 2018, FAO released *Sustainable Food Systems: Concepts and Frameworks*, emphasizing that environmental sustainability hinges on ensuring food system activities have positive or neutral impacts on the natural environment (FAO, 2018). In 2021, FAO issued its *Strategic Framework 2022-2031* to guide agrifood systems transformation, focusing on efficiency, inclusivity, resilience, and sustainability, and aiming to deliver better production, nutrition, environment, and livelihoods. Its overarching goal is to ensure progress for all while leaving no one behind (FAO, 2021). In 2022, FAO released its *Climate Change Strategy 2022-2031*, prioritizing reductions in ecosystem conversion, farm energy use, food loss, and waste. The strategy aspires to establish a low-emission and climate-resilient food system as quickly as possible (FAO, 2022).

FAO has placed agrifood systems transformation at the center of global climate agendas and actions. At the 27th UN Climate Change Conference (COP27), FAO explicitly emphasized the sector's critical role, and at COP28, it launched a *Global Roadmap for Achieving Sustainable Development Goal 2 (SDG2) without Breaching the 1.5°C Threshold*, identifying 120 actions and key milestones across 10 domains, aiming to reduce GHG emissions from agrifood systems by 25% by 2030, and achieve carbon neutrality by 2035. Ultimately, it seeks to transform these systems from net emission sectors into net carbon sinks by 2050[3]. FAO also supports programs such as *Scaling Up Climate Ambition for Land Use and Agriculture through Nationally Determined Contributions and National Adaptation Plans (SCALA)* and *Strengthening Agricultural Adaptation (SAGA)* to advance global climate actions in the sector (FAO, 2023).

The United Nations Framework Convention on Climate Change (UNFCCC) has incorporated agrifood systems emissions reduction into its climate agenda. At COP26 in 2021, 137 countries signed the *Glasgow Leaders' Declaration on Forests and Land Use*, committing to halt and reverse deforestation by 2030[4]. Additionally, over 100 countries joined the *Global Methane Pledge* to reduce methane emissions, including emissions from the agricultural sector by 30% by 2030[5]. COP27 emphasized agriculture and food security as a key issue, launching initiatives such as the *Sustainable Transformation of Food and Agriculture Initiative* and the *Climate Action and Nutrition Initiative*[6].

COP28 marked a breakthrough in positioning agrifood systems within international climate cooperation (Fan and Zhang, 2024). For the first time, a "Food, Agriculture and Water" theme day was established. A total of 134 countries, representing 5.7 billion people, 70% of global food production capacity, and 76% of GHG emissions from agrifood systems, signed the *UAE Declaration on Sustainable Agriculture, Resilient Food Systems and Climate Action*. This is the first global declaration linking agrifood systems directly to climate action, committing signatories to integrate these systems into their national climate agendas by 2025. The declaration also aims to reduce GHG emissions while safeguarding the livelihoods of farmers most vulnerable to climate change. The UAE presidency announced that over $2.5 billion had been mobilized to support food security, address climate change, and advance innovations in agrifood systems transformation. Additionally, a coalition of non-state actors, farmers, frontline communities, businesses, NGOs, cities, and consumers, launched the *Food Systems Call to Action* to jointly pursue goals of human well-being, nature conservation, and climate action[7].

COP29 in 2024 carried forward the agrifood

[1] https://cn.ifpri.org/archives/7302

[2] https://www.un.org/zh/food-systems-summit/about

[3] https://www.fao.org/interactive/sdg2-roadmap/en/

[4] https://webarchive.nationalarchives.gov.uk/ukgwa/20230418183423/

[5] https://ukcop26.org/the-glasgow-climate-pact/

[6] https://unfccc.int/topics/land-use/workstreams/agriculture#SB-62-June-2025

[7] https://climatechampions.unfccc.int/the-food-systems-call-to-action/

systems agenda established at COP28, urging calling on countries to fully integrate the sector into their NDCs. The "Food, Agriculture and Water" theme day focused on fostering collaboration among stakeholders to address food system challenges. The *Declaration on Reducing Methane from Organic Waste* was launched on the same day, with over 30 countries, including the United States, Canada, and Mexico, which together account for 47% of such emissions, committing to sector-specific emissions reduction targets. Additionally, the FAO and COP29 presidency jointly introduced the *Baku Harmoniya Climate Initiative for Farmers*, a platform to promote climate finance and accelerate agrifood systems transformation.

The World Bank has also played a leading role in promoting green, resilient, and inclusive agrifood systems development. As the largest provider of climate finance to developing countries, the World Bank supports poverty reduction while tackling climate change challenges in agrifood systems. Its investment projects cover climate adaptation, food security, ecosystem protection, clean energy transitions, and supply chain optimization[8]. The World Bank's *Climate Change Action Plans (CCAP)*, launched in 2016 and updated in 2021, have significantly expanded climate finance for agrifood systems. *CCAP (2016-2020)* aimed to increase the share of climate finance to 28% of total lending by 2020, designating agrifood systems as one of the six priority areas (WBG, 2016). Over $83 billion in climate finance was provided during the period, with the share of adaptation support growing from 40% in 2016 to 52% in 2020 (WBG, 2021). The updated *CCAP (2021-2025)* focuses on integrating climate and development goals across five priority sectors, including agrifood systems. It commits to raising climate finance to an average of 35% of total lending, with at least 50% allocated to climate adaptation. The plan facilitates sustainable agrifood systems transformation through multiple approaches, such as scaling up renewable energy systems, promoting climate-smart agriculture, investing in nature-based solutions, addressing food loss and waste, enhancing carbon sinks, and mobilizing private sector investment while reducing associated risks (WBG, 2021).

[8] https://www.worldbank.org/en/topic/climatechange/overview

1.1.2 Progress in Low-carbon Transformation of Global Agrifood Systems

The low-carbon transformation of agrifood systems requires a comprehensive, system-wide approach spanning the entire value chain, from production to consumption, addressing both supply and demand sides. It necessitates coordinated emission reduction and carbon sequestration actions across multiple sectors, including agriculture, ecosystems, industry, energy and transportation. Active participation from a wide range of stakeholders, such as governments, farmers, enterprises and consumers, is essential to achieve integrated and synergistic climate outcomes (Costa et al., 2022; Wang et al., 2025).

On the supply side, the transformation focuses on improving technologies and management practices, including production practices, methods, and patterns of energy use (Springmann et al., 2018; Qi et al., 2024). Key measures include enhancing agricultural energy efficiency, reducing energy consumption along the agrifood value chain, and transforming to non-fossil energy sources. Scaling up clean and renewable energy in agrifood production is also critical for reducing sectoral emissions (Chen et al., 2023; Searchinger et al., 2019; Grubler et al., 2018).

On the demand side, the focus is on reshaping consumer behavior to reduce GHG emissions. This includes minimizing food waste and loss, as well as shifting toward healthier and more environmentally sustainable diets (Springmann et al., 2018; Searchinger et al., 2019; Humpenöder et al., 2024).

For the Agriculture, Forestry, and Other Land Use (AFOLU) sector, protecting and restoring natural ecosystems and restricting the conversion of high-carbon-density lands are crucial for climate change mitigation. Additionally, prioritizing sustainable agricultural management, optimizing land use, and enhancing carbon sequestration strategies further contribute to these efforts (Searchinger et al., 2019; Clark and Tilman, 2017; Qi et al., 2024; Wang et al., 2025).

Throughout this transformation process, it is critical to ensure alignment with broader SDGs, particularly food security and the livelihoods of vulnerable groups. Such an integrated strategy ensures sustainable and inclusive growth while accelerating socioeconomic development

(Wang et al., 2025). This section will focus on the key areas of emission reduction and carbon sequestration in agrifood systems. It will systematically review the global progress in emission reduction of agrifood systems from the dimensions of rice cultivation, livestock husbandry, energy use, reduction of food loss and waste, and dietary structure transformation, and summarize the practical achievements of carbon sink enhancement in the AFOLU sector.

(1) Global Progress in Rice Cultivation GHG Emission Reduction

The international community has made breakthroughs in reducing GHG emissions from rice cultivation by improving water management, innovating planting pattern, enhancing soil and straw management technologies, and developing low-carbon variety.

One major breakthrough is the development and promotion of Alternate Wetting and Drying (AWD) irrigation technology, achieved through collaboration between the International Rice Research Institute (IRRI) and the National Agricultural Research and Extension Systems (NARES). AWD represents a transformative shift in water management by periodically drying rice paddies instead of continuous flooding. This practice substantially reduces methane and nitrous oxide emissions, lowering the global warming potential (GWP) by 26%-29% (Tran et al., 2018). Integrating "Optimal Organic N Management" with intermittent irrigation technology has effectively reduced net GHG emissions and GWP intensity in major producing regions such as China, India, and Africa (Liu et al., 2024).

AWD has been widely adopted in major rice-growing areas of Southeast Asia, including the Philippines, Vietnam, and Bangladesh. Japan has implemented an extended mid-season drying technique, which controls methane emissions effectively without sacrificing yields. To support its adoption, Japan released a *New Water Management Technology Manual for Suppressing Methane Emissions in Paddy Fields*[9]. In Africa, countries like Egypt have reduced methane emissions by optimizing rice planting areas to ensure rational water resource allocation[10].

Progress has also been made in optimizing cropping patterns. Compared with rice-wheat, ratoon rice, and double-cropping rice systems, the rice-oilseed rotation significantly reduces GHG emission intensity (Zhang et al., 2019; Chen et al., 2020; Li et al., 2022). Gao et al. (2025) estimate that optimizing planting patterns and resource management could increase global rice production by 36%, while reducing GHG emissions by 23% and nitrogen loss by 32%.

In addition, researchers have focused on promoting methane oxidation and inhibiting methanogenesis in paddy soils. For example, the combined application of phosphogypsum, biochar, and N-P-K-Zn fertilizers in saline-alkali soils promotes methane oxidation (Khatun et al., 2021). Meanwhile, a composite inhibitor made from cellulose acetate-ethephon can increase methane inhibition efficiency by up to 43% (Cho et al., 2022).

Improvements in straw management technologies have further contributed to reduce GHG emissions and soil enhancement. One approach involves removing straw from the field and converting it into molded fuel, replacing standard coal and reducing GHG emissions (Feng et al., 2022). Denmark pioneered straw-based power generation[11], and biomass energy has become increasingly common across the European Union[12]. Alternatively, technologies for carbonizing straw into biochar and returning it to the farmland to increase soil carbon storage (Zhu et al., 2024).

Varietal selection also plays a key role in mitigation. Bhattacharyya et al. (2019) found in India that methane emissions can vary by 5.7 times among different rice varieties, highlighting the potential for breeding low-emission rice varieties at the genotypic level. Recent advances include the development of OsbZIP1 gene-mutated rice by Tanaka et al. (2024) and China's Water-Drought Resistant Rice (WDR), both marking significant global progress in breeding low-emission, high-yield rice varieties.

At the global level, the international community launched the *AIM for Climate* in 2021, focusing on increasing investment in agricultural emission reduction technology research, development, and demonstration. As of 2023, this initiative has brought together 47 countries and over 400 institutions, raising more than 8 billion dollars in cumulative funding. It has supported 30 *Innovation Sprint* projects, with sustainable rice

[9] https://www.naro.affrc.go.jp/archive/niaes/techdoc/methane_manual.pdf
[10] https://unfccc.int/documents/204823
[11] https://www.ccchina.org.cn/Detail.aspx?newsId=19512&TId=58
[12] https://www.beipa.org.cn/newsinfo/7226534.html

production identified as a priority area (Boehm et al., 2023).

(2) Global Progress in Livestock GHG Emission Reduction

The global governance framework for livestock emission reduction is rapidly taking shape, entering a new stage marked by enhanced national climate commitments and the development of systematic mitigation pathways. Livestock production is a major source of GHG emissions in agrifood systems, with methane emissions from manure and enteric fermentation alone contributing approximately 32% of global methane emissions (UNEP and CCAC, 2021). Currently, more than one-third of countries have incorporated livestock-related mitigation measures into their climate commitments, and over half of the countries have identified livestock systems as a key area for agricultural adaptation (FAO, 2023).

The FAO has identified five practical actions for building low-emission livestock systems. First, improve the efficiency of livestock production and resource utilization. Second, enhance recycling efforts to minimize losses and achieve a circular bioeconomy. Third, leverage nature-based solutions to increase carbon offsets. Fourth, promote healthy and sustainable diets and explore protein alternatives. Fifth, develop policy measures to drive transformation (FAO, 2019).

Breakthrough technologies for reducing global livestock GHG emission are advancing rapidly. Integrated pasture management solutions have been successfully implemented in multiple countries. Key mitigation approaches include improving feed, enhancing ruminant digestibility, and optimizing pasture use.

To accelerate innovation, the Global Methane Hub has committed $200 million to launch the Enteric Fermentation R&D Accelerator funding program, which targets key areas such as feed additive development, low-emission livestock breeding, rumen microbiome research, methane vaccine innovation, and lowering cost of methane monitoring[13]. Among notable innovations, the feed additive 3-Nitrooxypropanol (3-NOP) has been shown to reduce methane emissions by an average of 30% and has now entered commercial use in several markets, including the EU, Australia and Brazil.

Animal breeding technologies are also making strides. New Zealand has successfully bred low-emission sheep, with the first batch of breeding materials possessing low-methane genetic traits released in 2023 (Boehm et al., 2023).

Manure management focuses on three key stages: manure collection, storage, and resource utilization (Zhang et al., 2023). For example, in the United States, manure management is a core component of agricultural methane reduction efforts, with initiatives including promoting anaerobic methane digesters and solid-liquid separators, implementing deep burial and composting practices, and encouraging renewable energy use on farms[14].

In pasture management, integrating measures such as feed optimization (high-quality forage, emission reduction additives and diet balance), animal health and nutrition management (veterinary care and precision nutrition), genetic breeding (low-emission varieties and improved reproductive efficiency), and sustainable grassland practices (rotational grazing, stocking rate regulation, integration of agriculture and animal husbandry) contributes to both emission reduction and productivity improvement.

Countries and regions including the United States, New Zealand, China, and Europe are advancing low-carbon livestock systems through optimized pasture management, as part of broader efforts to establish net-zero carbon emission demonstration pastures. The FAO is collaborating with countries in Africa, Asia, and Latin America to implement livestock emission reduction measures, identify best practices in pasture management, and scale successful models[15].

(3) Global Progress in Energy Transformation

The decarbonization of energy use in global agrifood systems has become a central priority. As agrifood systems remain heavily reliant on fossil fuels, accounting for approximately 30% of global energy consumption and nearly one-third of total GHG emissions, many countries have adopted policies to drive the energy transition (IRENA and FAO, 2021). Replacing

[13] https://www.globalmethanehub.org/2023/12/02/enteric-fermentation-research-development-accelerator-a-200m-agricultural-methane-mitigation-funding-initiative/

[14] https://www.whitehouse.gov/wp-content/uploads/2021/11/US-Methane-Emissions-Reduction-Action-Plan-1.pdf

[15] https://www.fao.org/in-action/enteric-methane/background/best-practices/en

fossil fuels with renewable energy is now a critical strategy for reducing GHG emissions across the agrifood value chain.

In 2011, the FAO launched the Energy-Smart Food Initiative to improve access to renewable energy in agrifood systems. The initiative focuses on enhancing energy efficiency, adopting renewable energy sources, converting agricultural waste into reusable energy, and implementing innovative green solutions that integrate water, energy, and food systems. At COP26, the International Renewable Energy Agency (IRENA) and FAO jointly released *Renewable Energy for Agriculture and Food Systems* at COP26, emphasizing the critical role of renewable energy in meeting the electricity, heating, cooling, and transportation needs throughout global agrifood systems (IRENA and FAO, 2021).

Notable progress has been made in the formulation and implementation of renewable energy policies at national and regional levels. For example, Australia's Renewable Energy Target, Brazil's RenovaBio and NDC, Canada's Clean Fuel Standard, the U.S. Renewable Fuel Standards, and the Renewable Energy Directive II (EU-RED II) in European Union all emphasize goals to increase renewable energy and drive decarbonization of energy systems. Some policies explicitly address potential environmental impacts and social trade-offs of renewable energy production (Nabuurs et al., 2022).

Across the agrifood value chain, the deployment of solar, bioenergy, wind, and hydropower is expanding steadily:

● In agricultural production sector, renewable energy has been widely used for irrigation, lighting and heating. Life-cycle emissions of solar irrigation systems are 95%-98% lower than those of grid-powered or diesel-driven water pumps (IRENA and FAO, 2021), and such systems are developing rapidly in developing countries. For example, India had deployed over 272,000 related systems by 2020 (IRENA and FAO, 2021). Agricultural photovoltaics (APV), employing an "agriculture-photovoltaic complementarity" model to optimize land use efficiency, is increasingly supported by government policies in countries including Japan, France, the United States, South Korea, and China (Schindele et al., 2017). In addition, wind and hydropower have significant potential in irrigation and rural electrification (Rahman et al., 2022). The ongoing electrification of agricultural machinery and rural grid modernization are further enabling green electricity transitions in food production.

● In circulation sector, the green transformation of logistics is gaining momentum. Solar-powered cooling systems are reducing food losses, improving market access, and achieving related emission reductions in Asia and Africa (IRENA and FAO, 2021). Other emerging technologies include biogas-powered refrigeration, eco-friendly low-GWP refrigerants, and electric light-duty vehicles (Chen et al., 2023).

● In food processing sector, renewable energy applications are growing. In Africa, solar energy is used to power grain mills; In Uganda, Sierra Leone, Myanmar, and Nepal, hydropower and biomass microgrids support processing operations. New Zealand's dairy industry and Iceland's fisheries rely on geothermal energy to meet both electricity and thermal needs (IRENA and FAO, 2021).

● In waste treatment sector, the conversion of agricultural residues, such as crop straw, livestock manure, food waste, and by-products from processing, into biogas is expanding. Biogas now provides sustainable energy for cooking, heating and other uses in diverse contexts including sugarcane, cassava and rice production, as well as slaughterhouses, food processing plants, and waste treatment facilities. Globally, an estimated 125 million people use biogas for cooking, mainly in China, Nepal, Vietnam, India, Bangladesh, and neighboring countries. For example, Vietnam's livestock biogas program built 290,000 biogas digesters from 2003 to 2020, helping address livestock manure management challenges while improving living conditions for over 1.7 million people (IRENA and FAO, 2021).

(4) Global Progress in Reducing Food Loss and Waste

The global framework for reducing food loss and waste has taken initial shape. The international community has actively pursued strategic goals, policy frameworks, legal regulations, action initiatives, and public-private partnerships to address food loss and waste—making notable strides in target-setting, measurement, and implementation.

Globally, approximately one-third of the food produced for human consumption each year (equivalent to 1.3 billion tonnes) is lost or wasted (FAO, 2011). Food loss in post-harvest and pre-retail stages exceeds

13%, while food waste at retail, food service, and household levels reaches 19%. These inefficiencies reflect suboptimal use of land, water, energy, and other resources throughout the food supply chain, and account for 8%-10% of global GHG emissions (Mbow et al., 2019).

In 2015, the UN integrated food loss and waste reduction into the SDGs. SDGs 12.3 aims to halve per capita global food waste at the retail and consumer levels and reduce food loss in production and supply chains by 2030. In support of this, the World Resources Institute (WRI) launched the *Champions 12.3 initiative* to accelerate progress through global public-private collaboration toward achieving SDGs 12.3[16].

In terms of target-setting, by the end of 2021, countries and regional blocs representing 55% of the global population had established targets consistent with SDGs 12.3. These include major economies such as the African Union, Argentina, Australia, China, the European Union, Indonesia, Japan, Malaysia, South Africa, the United Arab Emirates, the United Kingdom, the United States, and Vietnam. Among the world's 50 largest food companies, 39 had established relevant targets (Lipinski, 2022).

In terms of measurement and monitoring, a systematic monitoring and evaluation system for food loss and waste is taking shape. FAO and UNEP have respectively developed the Food Loss Index and the Food Waste Index, offering methodological leadership.. By the end of 2021, 19 countries, representing 12% of the global population, had conducted food loss and waste measurements. These include Argentina, Australia, Canada, Colombia, Denmark, Israel, Italy, Japan, Finland, Mexico, the Netherlands, New Zealand, Norway, Saudi Arabia, Slovenia, Spain, Sweden, the United Kingdom, and the United States. Among the world's 50 largest food companies, 28 conducted food loss and waste measurements, with 19 publicly reporting relevant information (Lipinski, 2022). Of the 248 suppliers and retailers involved in the Champions 12.3 initiative, 74% have established, and 54% publicly report multi-year data, achieving an average reduction of 15.4% in food loss and waste (Lipinski, 2024).

In terms of actions, as of 2024, 25 countries have incorporated food loss and waste reduction into their NDCs, up from 14% of global population coverage in 2018 to 35% by 2024 (Lipinski, 2024). Key strategies include legislative action, fiscal incentives, public engagement, and education (OECD, 2025). Notably, the European Union adopted binding targets in July 2023, requiring member states to reduce food waste by 10% in processing and manufacturing and 30% in retail and consumption by 2030[17], the first mandatory food waste reduction targets worldwide. Countries such as the United States, Canada, France, and Italy promote social food donations through tax incentives (OECD, 2025). Technological solutions include improved harvesting, storage, and processing technologies and infrastructure, food redistribution systems, food waste treatment technologies, and enhancing packaging (Yang et al., 2021).

For example, the Food Loss App (FLAPP) developed by the FAO aims to quantify crop losses at the micro level. This digital tool enables farmers, cooperatives and agribusinesses to identify loss-reduction strategies while supporting net-zero emission goals. This innovative technology has been applied in China and multiple African countries such as Ghana and Ethiopia[18]. The training programs introduced by FAO on better food handling, sorting and packaging practices have helped tomato growers in the Philippines reduce losses by 38%. In Trinidad, root crop growers have achieved a post-harvest loss rate of less than 5%[19]. In 2023, the U.S. Environmental Protection Agency introduced the "Wasted Food Scale" to prioritize food waste prevention and management strategies. This framework establishes a circular economy-based hierarchy for optimizing food redistribution and utilization.

(5) Global Progress in Dietary Structure Transformation

In 2019, FAO and the World Health Organization (WHO) jointly defined sustainable healthy diets as those that promote individual health and well-being while minimizing environmental impacts. Such diets should also be accessible, affordable, safe, equitable, and culturally acceptable to ensure broad adoption (FAO and WHO, 2019). Global dietary transformation now combines planetary health diets with region-specific

[16] https://www.wri.org/initiatives/champions-123

[17] https://food.ec.europa.eu/food-safety/food-waste/eu-actions-against-food-waste/food-waste-reduction-targets_en

[18] https://www.fao.org/platform-food-loss-waste/fao-flapp

[19] https://www.fao.org/newsroom/detail/tackling-food-loss-and-waste-from-the-farm-to-the-table-and-beyond/en

dietary models. Dietary transformation is a measure with high emission reduction potential on the demand side to address climate change (Pathak et al., 2022). This approach could reduce the social cost of GHG emissions by 41-74% by 2030 through sustainable food consumption patterns (FAO, IFAD, UNICEF, WFP and WHO, 2020). The planetary health diet proposed by the EAT-Lancet Commission in 2019 leads the global dietary structure transformation. It aims to enhance human health while minimizing the food system's environmental footprint (Willett et al., 2019; Humpenöder et al., 2024).

The UN Climate Change High-Level Champions have called for 40% of the global population needs to shift to dietary patterns more in line with planetary health diets by 2030. Such a shift could lower land, water, and biodiversity pressures and increase the 1.5°C carbon budget by 125 billion tonnes of CO_2eq by reducing non-CO_2 emissions from agriculture (Humpenöder et al., 2024). Meanwhile, other regional sustainable healthy dietary models have emerged globally, such as the Mediterranean diet, Nordic diet, traditional Japanese diet, and Jiangnan diet. These diets all emphasize plant-based foods as dietary staples while incorporating optimized animal-source food structures (Xia et al., 2023). The Mediterranean diet is widely practiced in southern European countries along the Mediterranean coast such as Greece, Spain, and southern Italy. The Nordic diet is formed based on the traditional eating habits of Denmark, Finland, Iceland, Norway, and Sweden. European policymakers have adopted multiple strategies to promote the Mediterranean and Nordic diets. The key measures include updating national dietary guidelines, implementing school meal initiatives, and advancing food labeling systems (Renzella et al., 2018). The Japanese government promotes the traditional Japanese diet through the Basic Plan for Food Education Promotion and the inheritance of "Washoku" culture. The Jiangnan diet, represented by the dietary patterns in Zhejiang, Shanghai, Jiangsu and other regions of China, is promoted through the Chinese Dietary Guidelines (Chinese Nutrition Society, 2021).

Governments are increasingly integrating climate considerations into nutrition policy. For example, the Danish government revised its dietary guidelines to include climate impact as a key consideration for the first time in 2021. The updated guidelines promote climate-friendly eating patterns, advising higher legume and vegetable intake alongside reduced meat consumption.

Cities are also leading innovation. The *Milan Urban Food Policy Pact* and C40's *Good Food Cities Accelerator* have showcased urban strategies for dietary shifts (Boehm et al., 2023). The Cool Food Pledge, jointly led by WRI and UNEP, aims to reduce food-related GHG emissions by 25% by 2030. It supports large food suppliers in offering more plant-based and climate-friendly options while maintaining customer satisfaction. By 2022, the initiative had achieved a 10% reduction in the intensity of food-related GHG emissions compared to the baseline (Boehm et al., 2023).

Meanwhile, the alternative protein sector, including plant-based meat analogues and cultured meat, is accelerating development (Mbow et al., 2019). Although still a small share of the market in high-income countries, sales continue to grow. Cultured meat has obtained regulatory approval and entered pilot commercialization in Singapore and the United States. In 2022, global public investment in alternative proteins rose to $635 million (Boehm et al., 2023).

(6) Global Progress in Carbon Sequestration in Agriculture, Forestry and Other Land Use (AFOLU)

The global ecosystem has enormous carbon sequestration potential. The IPCC has evaluated 20 key mitigation measures in the global AFOLU sector. Among them, protecting, improving the management of, and restoring ecosystems such as forests, wetlands, and grasslands have the greatest potential for emission reduction and carbon sequestration. These measures include reducing deforestation, afforestation, peatland, coastal wetland and grassland restoration, etc. These measures are expected to have high cost-benefit ratios. They can achieve an annual GHG emission reduction potential of 7.3 billion tonnes of CO_2eq (3.9-13.1 billion tonnes) when the cost per ton of CO_2eq does not exceed 100 US dollars (Nabuurs et al., 2022).

A global governance framework for ecosystem-based carbon sequestration is emerging, characterized by coherent policy systems, mechanism innovation, and multi-dimensional practices. It demonstrates an evolutionary trend of emphasizing both policy-driven and market-incentivized approaches, as well as synergistic effects of multi-dimensional ecosystems. Solutions have been developed in key areas such as forest carbon sink enhancement, sustainable soil management, and marine and grassland carbon sink development. The international community has also reached several landmark agreements, including the *Ramsar Convention on Wetlands*, the *Glasgow Leaders' Declaration on Forests and Land Use*, and the *Kunming-Montreal Global Biodiversity Framework* (Boehm et al., 2023).

Payment for Ecosystem Services (PES) has emerged as a key policy tool, with over 550 initiatives operating globally and annual transaction volumes estimated between $36-42 billion (Salzman et al., 2018). Carbon sinks from forests and land use are the most focused part of PES. As an important mechanism for carbon sink in forests and land use, the Reducing Emissions from Deforestation and Forest Degradation (REDD+) program has been launched in more than 50 countries. And over 350 projects have been implemented in tropical regions (Angelsen et al., 2018). During 2006-2017, REDD+ projects achieved emission reductions of 7.5 billion tonnes of CO_2eq. These reductions represented 95% of all AFOLU sector mitigation achieved by 2018 (Nabuurs et al., 2022).

Sustainable Soil Management (SSM) centered on enhancing soil organic carbon, includes measures such as fallow and no-tillage, cover crops, crop diversification, soil fertility management, agroforestry, crop rotation, and control of soil and water loss (FAO, 2019). Practices such as the climate-smart agroforestry systems in Honduras, the Carbon Farming Initiative in Australia, and carbon registries in the United States demonstrate that SSM can make significant contributions to global agricultural GHG emission reduction (FAO, 2019).

Grassland and marine carbon sinks represent emerging frontiers for global carbon sequestration. Among them, the United States, the European Union, Australia, Japan, and Portugal have conducted in-depth explorations in basic research, methodological systems, project pilots, and trading of grassland carbon sequestration (Li et al., 2021). Kenya's *Mikoko Pamoja* is the first mangrove carbon offset project linked to the global carbon market. It raises funds for mangrove planting and protection through the sale of carbon credits, while providing income sources for communities[20]. In 2024, China restarted its Certified Voluntary Emission Reduction program, with marine carbon sink methodologies included in the first batch of this initiative.

Market-based mechanisms are also being used to scale AFOLU sector sequestration. New Zealand, the United States, and Canada have set important examples in constructing market mechanisms to promote carbon sequestration in the AFOLU sector. Currently, while countries and regions including the European Union, New Zealand, Canada, the United States, and China have established Emissions Trading Systems (ETS), only New Zealand's ETS includes the AFOLU sector. It is also the world's only emissions trading program that assigns emission responsibilities and rights of the forestry sector to landowners. From 2025, New Zealand plans to start pricing agricultural emissions at the farm level and fertilizer emissions at the processing level, becoming the first nation to fully integrate agricultural GHGs into its carbon market.

Carbon offset mechanisms allow emitters to purchase credits from land-based sectors to compensate for their emissions. Notable programs include provincial schemes in Alberta and Quebec, Canada, and the long-running carbon offset credit program in California, the United States, have provided good practices. The latter encourages emission reduction actions in livestock, grasslands, rice cultivation, forestry, and other fields. From April 2015 to March 2020, Australia's Emissions Reduction Fund (ERF) contracted 158 million tonnes of CO_2eq through carbon credit auctions, mainly from land use, land use change, and forestry (LULUCF) sector (Henderson et al., 2020).

Carbon taxation is also gaining attention in the agriculture and food sector. The European Union implemented the Carbon Border Adjustment Mechanism (CBAM) on October 1, 2023, the world's first carbon tariff system. Initially covering six sectors (cement, electricity, fertilizers, steel, aluminum, and hydrogen), CBAM may later expand to agrifood-related products (Jin and Liu, 2024). In the later stage, some countries may follow the EU's practice and expand carbon tariffs to agrifood systems.

A landmark development occurred on June 24, 2024, when Denmark announced the world's first carbon tax livestock emissions, marking a significant step toward methane emission reduction. The tax will come into

[20] https://www.unep.org/news-and-stories/story/mangrove-conservation-kenyan-style

effect in 2030 at a rate of 300 Danish kroner per tonne of CO_2eq, increasing to 750 Danish kroner by 2035. During the transformation period, farmers will be entitled to a 60% income tax reduction, resulting in effective tax rates of 120 Danish kroner in 2030 and 300 Danish kroner in 2035[21]. This policy highlights growing momentum among developed countries to integrate agricultural GHG emissions into climate pricing frameworks.

1.1.3 Challenges in the Low-carbon Transformation of Global Agrifood Systems

As a critical component of climate change mitigation and adaptation, the low-carbon transformation of agrifood systems is gaining heightened prominence in global climate action. The international community has reached a strong consensus on its importance and urgency, driving accelerated strategic goal-setting, continuous refinement of policy frameworks, rapid development of technological solutions, and proliferation of initiatives. Nevertheless, global progress remains insufficient to address the current climate crisis. Key challenges persist, including inadequate international commitments, slow implementation, insufficient financing and investment, and the underdevelopment of supporting technologies.

(1) Inadequate International Commitments and Key Gaps in Strategic Focus

The low-carbon transformation faces a major barrier in insufficient international commitments, characterized by inconsistent target-setting and critical gaps in focus. First, countries worldwide are missing significant GHG emission reduction opportunities due to deficient commitments. Although most nations include agrifood systems in their NDCs, mitigation targets are typically subsumed within broader economy-wide goals, lacking dedicated planning and long-term strategic support (WWF, 2020). Approximately three-quarters of NDCs currently demonstrate only low-to-medium ambition levels for agrifood systems (Crumpler et al., 2024), with few detailing sector-specific targets and concrete actions (WWF, 2020).

Moreover, the principle of Common but Differentiated Responsibilities requires urgent implementation. Developed countries exhibit significant delays in fulfilling agrifood mitigation commitments and providing pledged financial and technological support to developing nations. Conversely, low-income and least-developed countries—bearing lower historical emission responsibility—often propose more ambitious agrifood mitigation targets in their NDCs (Crumpler et al., 2024). Regionally, Sub-Saharan Africa, Latin America, and the Caribbean show higher target ambition, while Europe, Central Asia, and Asia-Pacific region lag behind.

Finally, high-impact mitigation domains remain overlooked, creating substantial action gaps. Current national targets predominantly focus on agricultural production stages, while high-potential strategies—such as reducing food loss and waste and shifting toward sustainable diets—are widely neglected in climate actions (WWF, 2020). Consequently, less than half of agrifood systems GHG emissions are covered by NDC targets. This results in an emissions gap equivalent to 60% of agrifood systems GHG emissions and 20% of global GHG emissions. Specific coverage gaps include 82% of pre-production and post-production emissions, 66% of livestock emissions, 70% of nitrous oxide emissions, and 59% of methane emissions (Crumpler et al., 2024).

(2) Slow Progress in Low-carbon Actions and Subpar Outcomes

According to *The State of Climate Action 2023* reported by WRI, global progress in agrifood systems decarbonization significantly lags behind the 2030 climate targets. Current efforts must accelerate severalfold to meet the *Paris Agreement*'s 1.5°C mitigation pathway (Boehm et al., 2023).

On the supply side, agricultural production systems require simultaneously achieving GHG emission reductions, efficiency gains, and enhanced carbon sequestration while ensuring food security for a growing global population. First, total agricultural GHG emissions continue to rise. To meet the 2030 climate target, the GHG emission intensity[22] of agriculture must decline three times faster than current rates, from 700 g CO_2eq/1000 kcal in 2020 to 500 g CO_2eq/1000 kcal by 2030. Second, agricultural productivity improvements remain insufficient. Global crop yield growth has stagnated, requiring a tenfold acceleration to increase

[21] https://skm.dk/aktuelt/presse-nyheder/pressemeddelelser/regeringen-og-parterne-i-groen-trepart-indgaar-historisk-aftale-om-et-groentdanmark

[22] Agricultural GHG emission intensity is measured in grams of CO_2eq per 1,000 kcal of global food supply (Boehm et al., 2023).

from 6.6 t/ha in 2021 to the 2030 target of 7.8 t/ha. Although ruminant meat production efficiency has seen some improvement, it still needs to accelerate by 1.2 times to rise from 29 kg/ha in 2021 to 33 kg/ha by 2030. Third, progress in ecosystem carbon sequestration is critically lagging. Protection measures not only inadequate but have in some cases regressed. Deforestation must decrease four times faster, the accelerating loss of mangroves requires urgent reversal, while forest and mangrove restoration must accelerate by 1.5 and 10 times, respectively. Peatland degradation continues unchecked, with restoration efforts severely off-track.

On the demand side, global food loss and waste are worsening, while dietary shifts toward sustainability remain slow. Global food loss rates increased from 13.0% in 2016 to 13.2% in 2021, deviating sharply from the 2030 target of 6.5% (Boehm et al., 2023). According to UNEP's *Food Waste Index Report 2024*, consumer waste at retail, foodservice, and household levels is escalating, with per capita food waste rising from 120 kg in 2019 to 132 kg in 2022, far exceeding the 2030 target of 61 kg (UNEP, 2024). As of now, only 12% of the global population resides in countries with systematic food loss and waste measurement mechanisms.

Regarding dietary transformations, affordability remains a barrier. In low- and middle-income countries, the cost of healthy sustainable diets exceeds current consumption patterns by 18%-29% (Springmann et al., 2021). Moreover, global ruminant meat consumption must decline eight times faster, from 91 kcal/capital/day in 2020 to 79 kcal/capital/day by 2030. Regions like Australia and New Zealand (179 kcal/capital/day), South America (135 kcal/capital/day), and North America (107 kcal/capital/day) substantially exceed target levels, while consumption continues to rise significantly across parts of Asia and Africa, including China, further complicating the dietary transformation needed for climate goals.

(3) Insufficient Low-carbon Transformation Funding Amid Multiple Financing Barriers

Global efforts to decarbonize agrifood systems face substantial funding gaps and persistent structural financing obstacles. First, the scale and intensity of financial commitments are demonstrably inadequate. Although global climate finance has increased in recent years, the share allocated to agrifood systems has declined sharply relative to total flows (Crumpler et al., 2024). During 2019-2020, annual agrifood climate finance averaged $ 28.5 billion, representing only 4.3% of total global climate finance ($660.2 billion) (CPI, 2023). Public climate finance specifically directed toward sustainable agrifood systems[23] was even lower, averaging just $ 9.1 billion annually during 2020-2021 (GAFF, 2024). According to *The Triple Gap in Finance for Agrifood Systems* (FAO & CLIC), an estimated $ 201.5 billion per year is required by 2030 to meet NDC-related needs, while reducing GHG emissions and building climate resilience across agrifood systems would require $ 1.15 trillion annually. The current annual average of $ 28.5 billion is severely insufficient, bridging this gap demands a sevenfold increase to meet NDC targets and a fortyfold increase for broader system transformation (CPI and FAO, 2025).

Second, deep-rooted structural financing barriers impede effective financing. Regarding funding sources and instruments, agrifood climate finance remains heavily reliant on the public sector, with development finance institutions and government budgets contributing 85%. Private sector financing from commercial institutions and corporations accounts for only 12%. Financing instruments are similarly imbalanced: debt instruments (bonds, grants, subsidies, market-rate loans) exceed 80%, while equity financing represents a mere 4% (CPI, 2023). Furthermore, financial mechanisms are misaligned with the needs of low-carbon transformations, leading to inefficient capital allocation. Low-carbon agrifood projects often face high perceived risks, significant upfront capital requirements, long payback periods, and exposure to environmental uncertainties. These risk-return profiles limit investor interest, further compounded by financial institutions' limited capacity to evaluate the non-monetized environmental and social benefits of such projects. Access to affordable finance is especially constrained for smallholders and ecosystem service providers, due to a lack of bankable business models and scalable, investment-ready projects. Globally, 439 million small-scale producers invest approximately $ 368 billion annually (excluding labor costs) in climate actions (Hou Jones and Sorsby, 2023) yet receive only

[23] Projects related to agrifood systems beyond the agriculture, forestry, and fisheries sectors are excluded.

1.7% of global climate finance[24]. Additionally, most agricultural support policies, such as tariffs, quotas, and direct subsidies, ignore climate objectives, often generating unintended incentives that contribute to land degradation, biodiversity loss, and increased GHG emissions (FOLU, 2019).

(4) Incomplete Methodological Systems and Insufficient Technological Development and Application

The low-carbon transformation of agrifood systems faces two critical challenges: underdeveloped assessment frameworks and constrained technological innovation, dissemination, and adoption.

First, the absence of a comprehensive global system for accounting, monitoring, and evaluating GHG emissions in agrifood systems severely hampers the ability to track progress and assess performance in the low-carbon transition overall. GHG accounting in agrifood systems is inherently complex, yet standardized accounting methodologies are lacking. Significant disparities exist across countries and regions regarding inventory boundaries, technical methods, framework content, and data sources, resulting in poor comparability and limited interoperability. Many countries, particularly in the Global South, lack systematic GHG monitoring, reporting, and verification systems. Challenges like missing baseline data and insufficient assessment capacity severely constrain performance tracking and progress assessment. In the AFOLU sector, while methodologies for forest-based carbon sinks are relatively mature, carbon sink accounting for marine, grassland, cropland, and wetland ecosystems is insufficiently integrated into national GHG mitigation and carbon sequestration assessments (Feng and Qiu, 2024). Furthermore, although various international indicator frameworks exist for agrifood systems, they are often fragmented. A unified and dedicated indicator system capable of comprehensively capturing the status and progress of low-carbon transformation remains absent.

Second, the development and application of low-carbon technologies remain constrained by multiple barriers. From a technical feasibility standpoint, many emerging technologies lack localized validation and optimization, rendering them ill-suited for diverse national and regional conditions. Furthermore, emission reduction potentials are often assessed using non-standardized methods, creating uncertainty about real-world effectiveness. For instance, the long-term efficacy, practical feasibility, and public acceptance of enteric fermentation inhibitors require further validation; bioenergy production may pose risks of indirect land-use change and threaten food security (Nabuurs et al., 2022). Concerning cost-effectiveness, high upfront investment costs and uncertain economic returns, especially for developing countries, render some technologies economically unviable, impeding deployment. Technologies like manure anaerobic digestion and renewable energy require producers to adjust input usage (Nabuurs et al., 2022), while shifts towards sustainable healthy diets may increase consumer food expenditures (Humpenöder et al., 2024). Concurrently, the external nature of carbon reduction benefits and the absence of robust market incentives mean economic returns are often not immediately visible, reducing motivation for adoption. The diffusion of low-carbon technologies is further constrained by inadequate policy support, such as insufficient fiscal subsidies and tax incentives, coupled with underdeveloped extension services, shortages of specialized personnel, and lagging infrastructure and information systems, further constrain the diffusion efficiency of low-carbon technologies.

1.2 Progress and Challenges in the Low-carbon Transformation of China's Agrifood Systems

China attaches great importance to addressing climate change and actively fulfills international climate conventions. China was one of the first contracting parties to the UNFCCC and a signatory to the *Kyoto Protocol* and the *Doha Amendment*. In September 2016, it ratified the *Paris Agreement*, becoming the 23rd contracting party to complete the ratification process. To promote the achievement and implementation of the *Paris Agreement*, China pledged at the UN General Assembly in September 2020 to increase its NDC efforts and achieve a carbon peak before 2030 and carbon neutrality before 2060. In 2023, China signed the *UAE Declaration on Sustainable Agriculture, Resilient Food Systems and Climate Action*. The country has developed a low-carbon development strategy for agriculture and proposed new measures in its NDC to reduce GHG

[24] https://www.unfoodsystemshub.org/fs-stocktaking-moment/programme/food-systems-and-climate-action/en.

emissions, increase efficiency in agriculture, and enhance ecosystem carbon sequestration. These are making a positive contribution to the low-carbon transformation of agrifood systems.

1.2.1 Progress of Low-carbon Transformation in China's Agrifood Systems

The low-carbon transformation of agrifood systems is an essential foundation for achieving China's "dual-carbon" strategic goals and has significant implications for global climate governance. As a major producer, consumer, and exporter of agricultural and food products globally, China's agrifood systems generate considerable GHG emissions. According to FAO statistics, GHG emissions from China's agrifood systems increased by 77.05% in 2022 compared to 1990, reaching 2.342 billion tonnes of CO_2eq. The pre- and post-production stages are the primary sources of these emissions, accounting for 59.70%, while emissions from on-farm production contribute the remaining 40.30%. China's share of GHG emissions has increased from 8.7% in 1990 to 14.42% in 2022, highlighting its increasing importance in reducing emissions[25].

China is actively advancing its NDC targets and actions in response to the global climate crisis. In June 2015, China submitted the *Enhanced Actions on Climate Change: China's Intended Nationally Determined Contributions* to the UNFCCC, setting its NDC target by 2030 and proposing policy measures to implement its NDC target in key areas such as agriculture and forestry. In October 2021, China submitted to the UNFCCC the *China's Achievements, New Goals and New Measures for Nationally Determined Contributions*. The update proposed a range of implementation pathways for the low-carbon transformation of agrifood systems, including reducing GHG emissions and increasing efficiency in agriculture, consolidating and increasing ecosystem carbon sinks, promoting renewable energy, and developing green and low-carbon lifestyles.

Since 2015, China has attached great importance to agricultural green development, deploying systematic measures and steadily advancing its implementation. To address the environmental pollution caused by extensive agricultural production practices, the central government began implementing multiple policy reforms, including canceling support policies for the fertilizer industry, promoting zero-growth plans for fertilizers and pesticides, and providing subsidies for agricultural resources and ecological protection. These efforts have aimed to reduce chemical inputs and improve the utilization of agricultural waste. As a result, GHG emissions from agricultural production activities have decreased by about 4.0% by 2018 (AGFEP, 2021).

In 2020, China announced its goal of peaking carbon emissions before 2030 and achieving carbon neutrality by 2060, an ambitious international commitment. To implement the "dual- carbon" goal tasks, the central government has issued the *Working Guidance for Carbon Dioxide Peaking and Carbon Neutrality in Full and Faithful Implementation of the New Development Philosophy* and *The Action Plan for Carbon Dioxide Peaking by 2030*. These were followed by sector-specific strategies such as the agricultural green development, promoting green and low-carbon development in agriculture and rural areas.

In August 2021, the Ministry of Agriculture and Rural Affairs and six other agencies jointly issued the *14th Five-Year Plan for National Agricultural Green Development*, China's first special plan for agricultural green development, which clarifies the key tasks of agricultural green development. *Guiding Opinions on Coordinating and Strengthening Work Related to Responding to Climate Change and Protecting the Ecological Environment*, issued in 2021, explicitly propose the use of nature-based solutions to mitigate and adapt to climate change, and jointly promote the governance of mountains, waters, forests, farmland, lakes, and grasslands.

In May 2022, the Ministry of Agriculture and Rural Affairs and the National Development and Reform Commission jointly formulated the *Implementation Plan for Carbon Emission Reduction and Sequestration in Agriculture and Rural Areas*, which proposed six tasks including energy-saving and emission reduction in crop farming, emission reduction in animal husbandry, emission reduction and carbon sequestration in fisheries, carbon sequestration of farmland, energy-saving and emission reduction of agricultural machinery, and replacement with renewable energy. Additional policies, such as the *Chemical Fertilizer Reduction Action Plan*

[25] https://www.fao.org/faostat/en/#data/GT

by 2025 and the *Chemical Pesticide Reduction Action Plan by 2025,* have been launched to comprehensively promote the reduction of chemical fertilizers and pesticides.

The introduction and implementation of these policy instruments reflect China's determination to accelerate GHG emission reductions in its agrifood systems. This section will review China's progress of low-carbon transformation in agrifood systems across five key dimensions: agricultural production emission reduction, energy transformation, reduction of food loss and waste, dietary structure adjustment, and enhancement of carbon sequestration in the AFOLU sector.

(1) Progress in Reducing GHG Emissions in Agricultural Production

Rice cultivation is a major source of methane emissions in China, and China has achieved systematic breakthroughs in low-carbon rice production through technological innovation and policy system reform. According to *The People's Republic of China First Biennial Transparency Report on Climate Change,* methane emissions from rice cultivation reached 248 million tonnes of CO_2eq by 2021. In response to this challenge, China has prioritized rice methane emission reduction since 2021.

In 2021, the focus was on technical standardization. In November, the Ministry of Agriculture and Rural Affairs released the *Ten Key Technologies for Carbon Emission Reduction and Carbon Sequestration in Agriculture and Rural Areas*, which included methane mitigation technologies for rice paddy fields in the national technology catalog for the first time. In 2022, rice methane reduction efforts advanced to the stage of mechanism innovation. In January, the *Guiding Opinions on Promoting the Construction of Ecological Farms* proposed exploring methane-related low-carbon compensation policies using ecological farms as pilot platforms. In June, the *Implementation Plan for Carbon Emission Reduction and Sequestration in Agriculture and Rural Areas* identified methane reduction in rice paddies as one of the top ten actions, outlining three core measures for rice emission reduction, and initiating central-local coordination through implementation plans in provinces and cities such as Hunan, Beijing, Sichuan, and Shanxi.

By March 2023, the *Implementation Plan for Comprehensive Prevention and Control of Agricultural Non-point Source Pollution in the National Agricultural Green Development Pilot Zone* emphasized deep fertilization technology for rice. In November, the Ministry of Ecology and Environment, together with 11 other departments, issued the *Methane Emission Control Action Plan*, which for the first time specified methane reduction targets for rice cultivation by 2030.

At the technical level, China has established a climate-smart emission reduction technology system for rice, integrating innovative technologies such as the use of effective microorganisms (EM) to suppress methanogenic bacteria, straw decomposition techniques, low-carbon and high-yield rice varieties such as SUSIBA2, and intermittent irrigation methods for water-saving. These practices effectively reduce the methane emission intensity from rice fields and promote the transition towards green and low-carbon rice production (Qin et al., 2023). Research by the Crop Science Research Institute of the Chinese Academy of Agricultural Sciences shows that, through technological innovations such as expanding rice cultivation northward, promoting high-yield varieties, and employing water -saving tillage practices, China has achieved a 130% increase in rice yields while significantly reducing GHG emissions from rice paddies by 70% (Zhang et al., 2019).

China has also established a comprehensive governance system for reducing GHG emissions from livestock industry, driven by legal reforms, policy innovation, and optimization of technical pathways. The revision and implementation of the *Environmental Protection Law of the People's Republic of China* and the *Animal Husbandry Law of the People's Republic of China* in 2015 established a dual legal framework supporting both quantity and quality improvement in emissions control. On the technical side, standards such as the *Technical Specifications for Sanitation Treatment of Livestock and Poultry Manure* and the *Technical Guidelines for Construction of Fecal Treatment Facilities in Livestock and Poultry Farms (Households)* have been intensively released. Policy tools have evolved from traditional regulatory approaches to include technology promotion (such as the *Assessment Plan for the Resource Utilization of Livestock and Poultry Waste*), economic incentives (such as the *subsidies for the construction of manure treatment facilities*), and pilot demonstrations (such as the *Plan for Promoting the Pilot Utilization of Agricultural Waste Materials*).

In 2018, the release of the *Guidelines for Agricultural Green Development Technology (2018-2030)* marked a shift toward a systematic policy restructuring phase. These guidelines set quantitative goals for livestock industry: increasing feed conversion efficiency by 10% and reducing carbon emission intensity per unit output by 30% by 2030. With the implementation of the national "dual-carbon" strategy, livestock has become a key sector within the national carbon peaking action plan. In support, the Ministry of Agriculture and Rural Affairs introduced *Methods for calculating greenhouse gas emissions of livestock and poultry farm NY/T 4243-2022* to provide industry carbon measurement benchmarks.

The central government has also established dedicated support funds to promote livestock and poultry manure resource utilization in 723 counties. The *Methane Emission Control Action Plan* further refined collaborative technical pathways combining enteric fermentation regulation and manure management in ruminants. These comprehensive reforms have delivered tangible results. The resource utilization rate of livestock and poultry manure resources increased from 37% in 2010 to 75% in 2020, while the proportion of untreated fecal GHG emissions decreased significantly from 74% to 19.3% (Wei et al., 2024). The number of large and medium-sized biogas projects increased rapidly, from over 400 in 1994 to over 6970 in 2015, a 17 fold increase. By 2022, over 97% of large-scale livestock farms were equipped with manure treatment facilities (Chinese Academy of Agricultural Sciences and China Agriculture Green Development Research Society, 2024). The proportion of large-scale animal husbandry in total livestock production grew from 35% in 1994 to 71.5% in 2022, promoting the continuous reduction in GHG emissions intensity across the sector (Agricultural and Rural Carbon Peaking and Carbon Neutrality Research Center, Chinese Academy of Agricultural Sciences et al.., 2024).

(2) Progress in Energy Transformation

China has made notable strides in transforming the energy structure of its agricultural sector by advancing policy support, technological innovation, and regional pilot projects. These efforts have accelerated the development and deployment of renewable energy, expanded biomass energy applications, and driven various energy-saving agricultural projects.

The *Implementation Plan for Carbon Emission Reduction and Sequestration in Agriculture and Rural Areas* proposes to promote green energy consumption models such as biomass energy, solar energy, wind energy, and geothermal energy, tailored to local conditions, while increasing the supply of clean energy in rural areas.

The scale of renewable energy application is steadily increasing. By the end of 2024, China's total installed renewable energy capacity reached 1.889 billion kilowatts, a year-on-year increase of 25%, accounting for about 56% of China's total installed capacity. This includes 436 million kilowatts of hydropower, 521 million kilowatts of wind power, 887 million kilowatts of solar power, and 46 million kilowatts of biomass power. In 2024, national renewable energy power generation reached 3.46 trillion kilowatt- hours, an increase of 19% on a year-on-year basis, accounting for about 35% of the total power generation. Wind and solar power generation reached 1.83 trillion kilowatt-hours (up 27% year-on-year), while biomass power generation reached 208.3 billion kilowatt-hours (a 5% increase)[26].

By the end of 2022, China had 14.8 million household biogas systems in stock, with 4.16 million households actively using them. A total of 75111 biogas projects had been established, including 6553 large and extra-large projects. The bioenergy sector also saw the development of 64 bio-natural gas facilities, producing an annual output of 127.73 million cubic meters of bio natural gas[27]. By the end of 2023, biomass-based clean heating covered over 300 million cubic meters, with a total heating capacity exceeding 300 million gigajoules[28].

Innovative, energy-saving agricultural projects are also making a significant impact. The Yabuli and Yichun Three Industry Integration Demonstration Base Project in Heilongjiang Province applies biodynamic cycle farming and ecological emission-reduction technologies. The project includes a 200000-square-meter environmentally friendly pigsty, enabling the annual reuse of 50000 tonnes of straw and in-situ treatment of 50000 tonnes

[26] https://www.nea.gov.cn/20250221/e10f363cabe3458aaf78ba4558970054/c.html

[27] http://www.kjs.moa.gov.cn/hbny/202308/t20230818_6434594.htm

[28] https://beipa.org.cn/newsinfo/7147401.html

of manure, resulting in an annual carbon reduction of 17481.03 tonnes of CO_2[29].

Digital technologies are also enhancing precision in emission reduction. For instance, the water fertilizer integrated intelligent irrigation system developed by Xinjiang Huier Agricultural Group Co., Ltd. has reached a leading level in China. It has been promoted and used over 0.07 million hectares throughout Xinjiang, improving the utilization rate of functional fertilizers by more than 30% and achieving a water savings of about 20%[30].

(3) Progress in Reducing Food Loss and Waste

China has systematically promoted reducing food loss and waste, achieving phased results in improving mechanical harvesting, grain storage, and processing efficiency. Simultaneously, food waste reduction has been promoted through legislative action, such as the *Anti-Food Waste Law* and public initiatives like the "empty plate" campaign.

According to the *2023 China Food and Nutrition Development Report*, the total amount of food lost and wasted in China reached 460 million tonnes in 2022, causing economic losses of up to 1.88 trillion yuan, equivalent to 22.3% of the total agricultural output value. Losses and waste occur throughout the entire food supply chain, including production, post-production processing, storage, circulation, and consumption.

To address this challenge, China launched the "empty plate" campaign in 2013 to raise public awareness of food conservation. In 2016, China adopted a national plan for implementing the *2030 Agenda for Sustainable Development*, committing to halve global per capita food waste at the retail and consumer levels and reduce food losses along production and supply chains by 2030.

Since the 14th Five-Year Plan, China has systematically promoted reducing food loss and waste at both the legislative and operational levels. China promulgated the *Anti-Food Waste Law of the People's Republic of China* in 2021. The *Regulations on Grain Circulation* Management was amended, and the *Food Security Law of the People's Republic of China* was promulgated in 2023. In 2021 and 2024, the *Grain Conservation Action Plan* and *Grain Conservation and Anti-Food Waste Action Plan* further promoted long-term mechanism for food conservation and reinforced national efforts to tackle food loss and waste.

To implement the central deployment, the Ministry of Agriculture and Rural Affairs issued the *Guiding Opinions of the Ministry of Agriculture and Rural Affairs on Promoting Loss Reduction and Efficiency Improvement in the Processing of Agricultural Products*, *Notice of the General Office of the Ministry of Agriculture and Rural Affairs on Making Machine Harvesting Loss Reduction the Main Work of Grain Production Mechanization*, and *2022 Monitoring and Investigation Plan for Machine Harvesting Loss of Main Grain Crops* in 2020, 2021, and 2022, respectively, to further promote various aspect food loss reduction work.

The 2021 International Conference on Food Loss and Waste was successfully held in Jinan, Shandong Province, with participation from over 50 countries and international organizations. The conference released the *Jinan Initiative of the International Conference on Food Loss and Waste*, proposing key areas and directions for international cooperation in food loss reduction, providing valuable insights for global efforts.

Thanks to these comprehensive measures, China has achieved significant improvements across the grain supply chain. By 2023, the average machine harvest loss rates for wheat, rice, and corn had decreased to 1%, 2%, and 2.2%, respectively. Over the past decade, the post-harvest storage loss rate for farmers declined by approximately five percentage points. State-owned grain depots maintained a comprehensive internal storage loss rate within 1%. In grain processing, technologies such as flexible rice milling have boosted rice milling rate by 5% to 8%. In the catering industry and public institutions, the "empty plate" campaign has become a habit, with leftover packaging becoming more standardized and widespread.

(4) Progress in Dietary Structure Transformation

China is building a national framework to optimize nutrition and reshape dietary patterns, guiding citizens toward healthier, lower-carbon food choices. In 2020, food consumption accounted for 9% of China's total GHG emissions, reaching 1.18 billion tonnes of CO_2eq. Among them, 48% of GHG emissions stemmed from meat consumption. Rising demand for animal-sourced

[29] https://www.mee.gov.cn/xxgk2018/xxgk/xxgk06/202502/t20250212_1102102.html

[30] https://www.moa.gov.cn/xw/qg/202110/t20211019_6379788.htm

foods is exerting increasing pressure on natural resources and the environment, and food-related emissions are projected to reach 1.28 billion tonnes of CO_2eq by 2030 (AGFEP et al., 2023).

Over the past decade, China has introduced a series of policies and action plans to steer dietary change:

● 2014-*Outline of China's Food and Nutrition Development (2014-2020)*. Prioritized adequate supply, a balanced food structure and better nutrition.

● 2016-*Outline of the Healthy China 2030 Plan*. Launched a "Rational Diet" initiative, mandating a national nutrition plan, research on food-nutrition functions, public education, and population-specific dietary guidelines.

● 2019-*Healthy China Program (2019-2030)*. Designated "Rational Diet Action" as one of its flagship programs, setting measurable targets for health outcomes, nutrition literacy, food-supply security and dietary optimization.

● 2025-*Outline of China's Food and Nutrition Development (2025-2030).* Calls for nutrition-led, green development and the establishment of balanced, healthy eating patterns.

China has also issued four successive editions of its *Dietary Guidelines for Chinese Residents* (first in 1989, most recently in 2022). The 2016 and 2022 editions recommend:

● Diverse food intake with an emphasis on vegetables, fruit, whole grains, soy and dairy

● Moderate consumption of fish, poultry, eggs and lean meat

● Limited salt, oil and sugar

Modelling indicates that widespread adoption of these guidelines would substantially reduce diet-related GHG emissions (AGFEP et al., 2021; 2023).

The *Scientific Research Report on Dietary Guidelines for Chinese Residents (2021)* released in 2021 highlighted the Jiangnan region's diet, prevalent in Zhejiang, Shanghai, Jiangsu, as an Eastern exemplar of a healthy dietary pattern (Chinese Nutrition Society, 2021). This healthy dietary pattern has benefits for environmental sustainability (Xia et al., 2023; Wang et al., 2025).

Through this blend of strategic planning, legislation and evidence-based guidance, China is laying the groundwork for a dietary transition that supports both public health and national carbon-reduction goals.

(5) Progress in Enhancing Carbon Sequestration in Agricultural, Forestry, and Other Land Use (AFOLU)

China has formulated comprehensive development plans and systematically deployed efforts to enhance carbon sequestration in the AFOLU department. The *14th Five-Year Plan for National Agricultural Green Development* clearly proposes to comprehensively promote agricultural green development by 2025, with significantly enhancing emission reduction and carbon sequestration capacity identified as one of the critical development goals. The *Implementation Plan for Carbon Emission Reduction and Sequestration in Agriculture and Rural Areas* proposes to further consolidate and expand the carbon sequestration function of ecosystems by implementing protective tillage and other measures such as conservation tillage. In addition, the *Master Plan for the Major Projects for the Protection and Restoration of National Key Ecosystems (2021-2035)* and the *Implementation Plan for Consolidating and Enhancing Ecosystem Carbon Sequestration Capacity* provide long-term strategic guidance for expanding carbon sinks across the AFOLU sector.

Substantial progress has been made in boosting carbon sinks from agriculture and forestry and restoring grassland ecosystems, resulting in net GHG absorption. According to *The People's Republic of China First Biennial Transparency Report on Climate Change*, total GHG absorption of farmland, forest land, and grassland in China reached 1.047 billion tonnes of CO_2eq in 2021, an increase of 63.6% compared to 2005.

In cropland carbon sequestration, China has significantly improved soil carbon sequestration capacity by promoting conservation tillage, straw returning, organic fertilization, and crop rotation and fallow practices. In 2021, cropland carbon sequestration reached 106 million tonnes of CO_2eq, 2.58 times the 2005 level. From 2020 to 2024, the central government allocated 14.4 billion yuan to support 27.07 million hectares of black soil conservation tillage across the four northeastern provinces, with over 0.07 million hectares in 34 counties[31].

In the forestry sector, large-scale afforestation, forest protection, and forestry carbon sequestration projects have dramatically expanded carbon sinks. Through

[31] https://www.gov.cn/yaowen/shipin/202502/content_7003517.htm

initiatives such as the Natural Forest Protection Project and the Grain for Green Project, China's forest area reached 231 million hectares by 2022, with the forest coverage rate rising to 24.02%. As of 2023, total forest carbon storage reached 9.2 billion tonnes, with annual sequestration exceeding 200 million tonnes. Forest ecosystems account for 700-800 million tonnes of carbon sink per year — more than 80% of total terrestrial carbon sink in China[32].

In grassland restoration, since the start of the 14th Five-Year Plan, China has consistently improved over 2.67 million hectares of grassland annually, stabilizing degraded areas. In the Three-North Shelterbelt region, nearly 46.67 million hectares of grasslands have been rehabilitated, accounting for 70% of the national total. Nationwide, comprehensive vegetation cover in grasslands remains over 50%[33]. In 2021, the total GHG absorption from grasslands reached 64 million tonnes of CO_2eq, an increase of 34.3% compared to 2005.

1.2.2 Challenges in the Low-carbon Transformation of China's Agrifood Systems

Although China has introduced various environmentally friendly agricultural policies and measures since 2015 and achieved initial results, the emission reduction effect of these policy measures is limited. The low-carbon transformation of agrifood systems still has a long way to go.

Firstly, efforts to reduce GHG emissions from agrifood systems are constrained by both low public awareness and a lack of strategic coordination. According to *The People's Republic of China First Biennial Transparency Report on Climate Change* released by the Ministry of Ecology and Environment in 2024, GHG emissions from agricultural activities in China in 2021 were 931 million tonnes of CO_2eq, an increase of 17.4% compared to 2018. Between 1990 and 2022, China's share of global GHG emissions from agrifood systems rose from 8.7% to 14.42%[34], significantly outpacing the global average, highlighting China's growing responsibility in global agrifood GHG emissions reduction. However, awareness of the importance of reducing GHG emissions in agrifood systems remains limited across sectors of society. Although the central and various departments have proposed plans, essential tasks, significant actions, and safeguard measures for agricultural and rural GHG emissions reduction since 2020, the overall approach lacks coherence and synergy. At the same time, due to the involvement of multiple government agencies, effective cross-departmental collaboration is needed to balance diverse objectives such as food security, nutrition, health, and the increase in farmers' income. This complexity makes it difficult to fully integrate agrifood systems into the national climate strategies.

Secondly, the supporting methodological framework for low-carbon transformation of agrifood systems is still underdeveloped. Measuring and verifying carbon emission reductions and carbon sequestration in agrifood systems is complex, hindering the development of methodological support for the incentive mechanisms. Although China has successively released national information bulletins, data on agrifood systems' GHG emissions remain delayed and incomplete. Challenges include unclear accounting boundaries, difficulty in quantifying carbon emission reductions and sequestration, and the presence of over 200 million small farmers whose decentralized production further complicates monitoring and accounting. These constraints make it challenging to include small farmers in the carbon trading market or allow them to benefit from carbon reduction initiatives.

Thirdly, current support policies for low-carbon transformation are largely concentrated on the agricultural production, with insufficient attention to the pre- and post-production stages. Due to the long industrial chain of agrifood systems, the participating entities include small farmers and wholesale and retail, logistics, processing, and catering enterprises. The reduction of GHG emissions in the farming and food system requires the active participation of multiple stakeholders at all stages and the promotion of GHG emissions reduction throughout the entire chain. However, at present, most of the green support policies for agriculture focus on the agricultural production process, and rarely provide incentives for participants in the entire industry chain, which affects the emission reduction process of the farm food system. Additionally,

32 https://www.forestry.gov.cn/c/www/ggzyxx/364446.jhtml

33 https://www.forestry.gov.cn/c/www/lcdt/605958.jhtml

34 https://www.fao.org/faostat/en/#data/GT

the market share of ecological carbon sequestration projects in China's voluntary carbon market is relatively low, and trading mechanisms for ecosystem-based carbon credits are underdeveloped, restricting the full utilization of agrifood systems' sequestration potential.

Finally, the research, development, and promotion of low-carbon technologies remain insufficient, and their potential for emission reduction and carbon sequestration has not been fully realized. Existing agricultural technologies primarily focus on boosting productivity, with less attention given to climate change mitigation and carbon sequestration. For example, farmland and grassland ecosystems contribute less to carbon sequestration compared to forests, and research on relevant technologies remains limited. Even where such technologies exist, high implementation costs hinder large-scale adoption. Some mitigation measures may also introduce trade-offs: for instance, conservation tillage can reduce GHG emissions but may lead to increased weed and pest pressure in the early stages and be incompatible with conventional seeding equipment (Xu, 2022; Lal, 2015; Kienzler et al., 2012). Similarly, practices like no-till farming and straw incorporation can raise the risk of soil acidification, potentially reducing grain yields in the short term and undermining technology adoption (Liang et al., 2023; Zhao et al., 2022). Furthermore, smallholders often lack the capacity and motivation to adopt mitigation technologies, resulting in low uptake across the sector.

1.3 Strategies for Promoting the Low-carbon Transformation of Future Agrifood Systems

Despite facing multiple challenges, China's agrifood systems hold substantial potential for GHG emission reduction. Accelerating their low-carbon transformation will require greater awareness, strengthened cross-sectoral collaboration, and integrated efforts spanning policy development, technological innovation, institutional reform, and international cooperation.

(1) Elevating Awareness and Formulating National Strategies & Action Plans

The low-carbon transformation of agrifood systems constitutes a complex and systematic undertaking requiring societal recognition and a robust governance framework centered on government leadership and multi-stakeholder collaboration. Given its cross-sectoral nature, spanning agriculture, energy, nutrition, ecology, environment, and finance, a central inter-ministerial coordination body must be established to integrate efforts, guide low-carbon development, and jointly formulate national strategies and action plans. These plans must include clear, measurable GHG emission reduction targets while safeguarding food security.

As the transformation encompasses the entire food chain from production to consumption, strategy development must adopt collaborative governance principles. This entails clearly defining responsibilities and leveraging the critical roles of enterprises, cooperatives, and citizens in emission reduction across all stages. Public engagement mechanisms, promoting clean production, food waste reduction, and sustainable healthy diets, should be embedded within transformation frameworks through enhanced media outreach, knowledge dissemination, and public education. Such efforts will elevate public understanding of the transformation's necessity, urgency and importance.

Moreover, robust GHG monitoring and accounting systems for agrifood systems must be developed, with standardized methodologies, rigorous emission metrics, alongside a comprehensive evaluation index system. This will provide the technical foundation for domestic governance and bolster China's leadership in global agrifood systems decarbonization.

(2) Establishing a Policy Support System to Promote Low-carbon Transformation in Agrifood Systems

Given the significant environmental benefits of GHG emission reduction and carbon sequestration, policy tools must extend across the entire agrifood value chain. A diversified and integrated policy framework should be developed to promote low-carbon transformation, combining incentive-based measures, such as fiscal subsidies, tax relief, and financial mechanisms, with regulatory instruments. Infrastructure upgrades, such as high-standard farmland and water-saving irrigation facilities, should be prioritized to support low-carbon practices.

Policy orientation must shift fundamentally: phasing out subsidies for high-emission inputs and products in favor of low-emission alternatives. Enterprises adopting green production practices should benefit from preferential tax policies and credit terms to stimulate the widespread adoption of sustainable technologies. Furthermore, institutional mechanisms for ecological carbon sink markets must be improved, with enhanced support for carbon sequestration projects to fully leverage market forces in agricultural carbon mitigation.

(3) Accelerating Development and Diffusion of Efficient Green Win-Win Technologies

Technological innovation must be the driving force behind GHG mitigation in agrifood systems. Research and development should prioritize synergistic win-win technologies, including climate-resilient, high-yield, low-emission crop varieties, diversified feed sources and additives, and advanced techniques for sustainable crop and livestock production. Increased investment is needed for developing and demonstrating soil carbon enhancement methods, such as no-till farming, reduced tillage, crop rotation, and rotational grazing, to maximize agricultural carbon sequestration potential.

Special attention should be given to the integration of artificial intelligence in agriculture, especially "AI+ agriculture" and climate-smart production models. Integrating big data analytics into precision field management and livestock operations can simultaneously enhance productivity while reducing GHG emissions. Wider adoption of low-carbon technologies must be incentivized across the value chain, including input-efficiency technologies for fertilizer and pesticide reduction, orchard and tea plantation carbon-sink systems, and waste recycling and resource recovery solutions that augment agricultural carbon sequestration capacity.

(4) Strengthening Institutional Innovation to Mobilize Multi-Stakeholder Participation in Low-carbon Transformation

China's predominantly smallholder-based agricultural structure increases both the costs and complexity of emission reduction within the agrifood systems while hindering producer participation in carbon markets. Institutional innovation is urgently needed to incentivize diverse stakeholders, including private enterprises, socialized service systems, and emerging agricultural business entities, to actively engage in GHG emission reduction and carbon sequestration.

Such innovation must transcend the limitations of small-scale farming by establishing collaborative mechanisms that link private sectors with dispersed producers. This integration will enable smallholders to participate in carbon markets and share the economic benefits of mitigation efforts, thereby strengthening their motivation for sustained emission reduction. Concurrently, consumers should be engaged as active participants in carbon neutrality initiatives, with enterprises playing a more significant role in guiding households toward reducing food waste and adopting climate-friendly diets.

(5) Enhancing International Collaboration for the Low-carbon Transformation of Agrifood Systems

Climate change represents a shared global challenge requiring concerted international cooperation in finance, trade, and investment. China should actively engage in global efforts to accelerate low-carbon transformations within both its domestic and international agrifood systems. Domestically, China must draw on international expertise by strengthening collaboration with institutions like the FAO and Consultative Group on International Agricultural Research (CGIAR). This includes enhancing capacity building, organizing and participating in large-scale scientific initiatives related to agrifood systems decarbonization, and assimilating global best practices in GHG emission reduction technologies. Internationally, China should establish cooperative strategies with key trading partners to develop green, low-carbon supply chains, advancing systemic transformations across borders. Furthermore, China should proactively document its transformation experiences, actively contribute to global dialogues, and offer its unique model as a reference for promoting low-carbon transformation of agrifood systems worldwide.

References

Amahnui, G. A., Vanegas, M., Verchot, L., et al. 2025. Achieving the paris agreement goals by transitioning to low-emissions food systems: A comprehensive review of countries' actions. Environmental Science & Policy, 163, 103968.

Angelsen, A., Martius, C., De Sy, V., et al. 2018. Transforming REDD+: Lessons and new directions. CIFOR-ICRAF.

Babiker, M., Berndes, G., Blok, K., et al. 2022. Cross-sectoral perspectives. In IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and

New York, NY, USA.
Bhattacharyya, P., Dash, P. K., Swain, C. K., et al. 2019. Mechanism of plant mediated methane emission in tropical lowland rice. Science of the Total Environment, 651, 84-92.
Boehm, S., Jeffery, L., Hecke, J., et al. 2023. State of Climate Action 2023. Berlin and Cologne, Germany, San Francisco, CA, and Washington, DC: Bezos Earth Fund, Climate Action Tracker, Climate Analytics, Climate Works Foundation, New Climate Institute, the United Nations Climate Change High-Level Champions, and World Resources Institute.
Cho, S. R., Verma, P. P., Das, S., et al. A new approach to suppress methane emissions from rice cropping systems using ethephon. Science of the Total Environment, 804, 150159.
Clark, M. A., Domingo, N. G. G., Colgan, K., et al. 2020. Global food system emissions could preclude achieving the 1.5° and 2°C climate change targets. Science, 370(6517), 705-708.
Clark, M., Tilman, D. 2017. Comparative analysis of environmental impacts of agricultural production systems, agricultural input efficiency, and food choice. Environmental Research Letters, 12(6), 064016.
Costa, C., Wollenberg, E., Benitez, M., et al. 2022. Roadmap for achieving net-zero emissions in global food systems by 2050. Scientific Reports, 12(1), 15064.
CPI and FAO. 2025. The Triple Gap in Finance for Agrifood Systems. Revised. Rome. https://doi.org/10.4060/cd3611en.
CPI. 2023. Landscape of Climate Finance for Agrifood Systems. Available at: https://www.climatepolicyinitiative.org/wp-content/uploads/2023/07/landscape-of-climatefinance-for-agrifood-systems.pdf.
Crippa, M., Solazzo, E., Guizzardi, D., et al. 2021. Food systems are responsible for a third of global anthropogenic GHG emissions. Nature Food, 2(3), 198-209.
Crumpler, K., Wybieralska, A., Roffredi, L., et al. 2024. Agrifood systems in nationally determined contributions: Global analysis-Key findings. Rome, FAO. https://doi.org/10.4060/cd3210en.
FAO and WHO. 2019. Sustainable healthy diets-Guiding principles. Rome.
FAO, IFAD, UNICEF, WFP and WHO. 2020. The State of Food Security and Nutrition in the World 2020. Transforming food systems for affordable healthy diets. Rome, FAO. https://doi.org/10.4060/ca9692en.
FAO. 2011. Global food losses and food waste-Extent, causes and prevention. Rome.
FAO. 2018. Sustainable food systems: Concept and framework. Rome.
FAO. 2019. Five practical actions towards low-carbon livestock. Rome.
FAO. 2019. Recarbonization of global soils - A tool to support the implementation of the Koronivia Joint Work on Agriculture. Rome.
FAO. 2021. FAO Strategic Framework 2022-31. Rome.
FAO. 2022. FAO Strategy on Climate Change 2022-2031. Rome.
FAO. 2023. Agrifood solutions to climate change-FAO's work to tackle the climate crisis. Rome. https://doi.org/10.4060/cc8055en.
FOLU. 2019. Growing Better: Ten Critical Transitions to Transform Food and Land Use.
Gao, Y., Cui, J., Zhang, X., et al. 2025. Cost-effective adaptations increase rice production while reducing pollution under climate change. Nature Food,1-13.
Global Alliance for the Future of Food (GAFF). 2024. Public Climate Finance for Food Systems Transformation (2024 update). N.p.: Global Alliance for the Future of Food.
Grubler, A., Wilson, C., Bento, N., et al. 2018. A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies. Nature Energy, 3(6), 515-527.
Henderson, B., Frezal, C., Flynn, E. 2020. A survey of GHG mitigation policies for the agriculture, forestry and other land use sector.
Hou Jones, X., Sorsby, N. 2023. The unsung giants of climate and nature investment: Insights from an international survey of local climate and nature action by smallholder forest and farm producers. IIED, London.
Humpenöder, F., Popp, A., Merfort, L., et al. 2024. Food matters: Dietary shifts increase the feasibility of 1.5°C pathways in line with the Paris Agreement. Science Advances, 10(13), eadj3832.
IFPRI. 2022. 2022 Global Food Policy Report: Climate Change and Food Systems. Washington, DC: International Food Policy Research Institute.
IRENA and FAO. 2021. Renewable energy for agrifood systems-Towards the Sustainable Development Goals and the Paris agreement. Abu Dhabi and Rome. https://doi.org/10.4060/cb7433en.
Karl, K., Tubiello, F. N., Crippa, M., et al. 2024. Harmonizing food systems emissions accounting for more effective climate action. Environmental Research: Food Systems, 2(1), 015001.
Khatun, L., Ali, M. A., Sumon, M. H., et al. 2021. Mitigation rice yield scaled methane emission and soil salinity stress with feasible soil amendments. Journal of Agricultural Chemistry and Environment, 10(1), 16-36.
Kienzler, K. M., Lamers, J. P. A., McDonald, A., et al. Con-

servation agriculture in Central Asia—What do we know and where do we go from here? Field Crops Research, 2012, 132, 95-105.

Lal, R. 2015. Sequestering carbon and increasing productivity by conservation agriculture. Journal of Soil and Water Conservation, 70(3), 55A-62A.

Liang, F., Li, B., Vogt, R. D., et al. Straw return exacerbates soil acidification in major Chinese croplands. Resources, Conservation and Recycling, 2023, 198, 107176.

Lipinski, B. 2022. SDG Target 12.3 on Food Loss and Waste: 2022 Progress Report. Washington, DC: Champions 12.3.

Lipinski, B. 2024. SDG Target 12.3 on Food Loss and Waste: 2024 Progress Report. Washington, DC: Champions 12.3.

Liu B, Guo C, Xu J, et al. Co-benefits for net carbon emissions and rice yields through improved management of organic nitrogen and water.Nature food,2024,5(3):241-250.

Pathak. M., Slade, R., Shukla, P.R., et al. 2022. Technical Summary. In: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, NY, USA.

Mbow, C., Rosenzweig, C., Barioni, L.G., et al. 2019. Food Security. In: Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. Cambridge: Cambridge University Press.

Nabuurs, G-J., Mrabet, R., Abu Hatab, A., et al. 2022. Agriculture, Forestry and Other Land Uses (AFOLU). In IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, NY, USA.

OECD. 2025. Beyond food loss and waste reduction targets: Translating reduction ambitions into policy outcomes, OECD Food, Agriculture and Fisheries Papers, No. 214, OECD Publishing, Paris, https://doi.org/10.1787/59cf6c95-en.

Qi, X., Huang, X., Zhong, H., et al. 2024. Spatiotemporal drivers of food system GHG emissions in China. Resources, Conservation and Recycling, 205, 107580.

Rahman, M. M., Khan, I., Field, D. L., et al. 2022. Powering agriculture: Present status, future potential, and challenges of renewable energy applications. Renewable Energy, 188, 731-749.

Renzella, J., Townsend, N., Jewell, J., et al. 2018. What national and subnational interventions and policies based on Mediterranean and Nordic diets are recommended or implemented in the WHO European Region, and is there evidence of effectiveness in reducing noncommunicable diseases? Copenhagen: WHO Regional Office for Europe; (Health Evidence Network (HEN) synthesis report 58).

Riahi, K., Van Vuuren, D. P., Kriegler, E., et al. 2017. The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. Global Environmental Change, 42, 153-168.

Rosenzweig, C., Mbow, C., Barioni, L. G., et al. 2020. Climate change responses benefit from a global food system approach. Nature Food, 1(2), 94-97.

Rosenzweig, C., N Tubiello, F., Sandalow, D., et al. 2021. Finding and fixing food system emissions: The double helix of science and policy. Environmental Research Letters, 16(6), 061002.

Salzman, J., Bennett, G., Carroll, N., et al. 2018. The global status and trends of Payments for Ecosystem Services. Nature Sustainability, 1(3), 136-144.

Schindele, S., Trommsdorff, M., Schlaak, A., et al. 2020. Implementation of agrophotovoltaics: Techno-economic analysis of the price-performance ratio and its policy implications. Applied Energy, 265, 114737.

Searchinger, T., Waite, R., Hanson, C., et al. 2019. Creating a sustainable food future: A menu of solutions to feed nearly 10 billion people by 2050.

Springmann, M., Clark, M. A., Rayner, M., et al. 2021. The global and regional costs of healthy and sustainable dietary patterns: A modelling study. The Lancet Planetary Health, 5(11), e797-e807.

Springmann, M., Clark, M., Mason-D'Croz, D., et al. 2018. Options for keeping the food system within environmental limits. Nature, 562(7728), 519-525.

Tanaka, N., Yoshida, S., Islam, S. M., et al. 2024. OsbZIP1 regulates phosphorus uptake and nitrogen utilization, contributing to improved yield. The Plant Journal: For Cell and Molecular Biology, 118(1), 159-170.

Tran, H., Tokida, T., et al. 2018. Impacts of alternate wetting and drying on greenhouse gas emission from paddy field in Central Vietnam. Soil Science and Plant Nutrition, 64(1), 14-22.

UNEP and CCAC. 2021. Global Methane Assessment: Benefits and Costs of Mitigating Methane Emissions. Nairobi: United Nations Environment Programme.

UNEP. 2024. Food Waste Index Report 2024. Think Eat Save: Tracking Progress to Halve Global Food Waste. https://wedocs.unep.org/20.500.11822/45230.

Wang, X., Cai, H., Xuan, J., et al. 2025. Bundled measures for China's food system transformation reveal social and environmental co-benefits. Nature Food, 6(1), 72-84.

WBG. 2016. World Bank Group Climate Change Action Plan.

WBG. 2021. World Bank Group Climate Change Action Plan (2021-2025).

Wei, S., Fan, J., Tian, Y., et al. 2024. Low-carbon development policies and achievements in the context of the livestock sector in China. Frontiers of Agricultural Science and Engineering, 11(03):367-380.

Willett, W., Rockström, J., Loken, B., et al. 2019. Food in the Anthropocene: The EAT-Lancet Commission on healthy diets from sustainable food systems. The Lancet, 393(10170), 447-492.

WWF, UNEP, EAT and Climate Focus. 2020. Enhancing NDCs For Food Systems - recommendations for decision-makers.

Zhang, L., E, R., Ali, M. M., et al. 2023. Livestock And Poultry Manure Management From The Perspective of Carbon Neutrality in China. Frontiers of Agricultural Science and Engineering, 10(3), Article 3.

Zhang, Y., Jiang, Y., Tai, A. P., et al. 2019. Contribution of rice variety renewal and agronomic innovations to yield improvement and greenhouse gas mitigation in China. Environmental Research Letters, 14(11), 114020.

Zhao, X., He, C., Liu, W. S., et al. Responses of soil pH to no-till and the factors affecting it: A global meta-analysis. Global Change Biology, 2022, 28(1), 154-166.

Zhu, J., Luo, Z., Sun, T., et al. 2023. Cradle-to-grave emissions from food loss and waste represent half of total greenhouse gas emissions from food systems. Nature Food, 4(3), 247-256.

Chen, M., Hu, M., Yang, L., et al. 2023. The agrifood System and Carbon Neutrality: An Analysis of China's Agriculture- and Food-Related Greenhouse Gas Emissions and Emission Reduction Pathways.Beijing: Institute for Global Decarbonization Progress.

Chen, Y., Zhao, Y., Gao, D., et al.Effects of Different Rotation Patterns of Oil-Rice on Methane and Nitrous Oxide Emissions in Rice Fields. Environmental Science, 2020, 41(10), 4701-4710.

Fan, S., Zhang, Y 2024. Strategic Thinking on the Low-carbon Transformation of Agrifood Systems in China. Issues in Agricultural Economy, 12, 15-23.

Fan, S., Long, W., Feng, X., et al. 2022. The UN Food Systems Summit and Chinese Strategy. Issues in Agricultural Economy, 3, 4-16.

Feng, X., Qiu, H. 2024. International Experience and Inspiration in Realizing the Value of Ecosystem Services. World Agriculture, 4, 83-93.

Feng, X., Zuo, T., Sun, N., et al. 2022. Greenhouse gas emission reduction effect of a straw briquette central heating system. Chinese Journal of Eco-Agriculture, 30(04), 702-712.

Jin, S., Liu, Y. 2024. Research on Green Tools for Import Control of Agricultural Products——Insights From the EU Carbon Border Adjustment Mechanism. Rural Finance Research, 12, 3-12.

Li, C., Liu, Z., Gong, S., et al. 2022. Effects of Changing Rice Cropping Patterns on CH4and N2O Emissions from Paddy Fields. Ecology and Environmental Sciences, 31(5), 961-968.

Li, X., Zhang, H., Peng, W., et al. 2021. Recent Situation and Enlightenment of Crassland Carbon Sink in Some Developed Countries Journal of Forestry and Grassland Policy, 1(1), 91-96.

Qin, X., Wang, J., Wang, B., et al. 2023. Status of methane emissions from paddy fields, mitigation technologies and strategic pathways for low-carbon production. Climate Change Research, 19(05), 541-558.

Xia, J., Fan, S., Ding, X., et al. 2023. Development of Sustainable Healthy Diets in China. Strategic Study of CAE 25, 120-127.

Xu, Y. 2022. Conservation agriculture-mediated soil carbon sequestration: A review. Chinese Journal of Eco-Agriculture, 30(4), 658-670.

Yang, D., Han, J., Wang, Q., et al. 2021. International experience in reducing food loss and waste and its implications for China. World Agriculture, 6, 62-71.

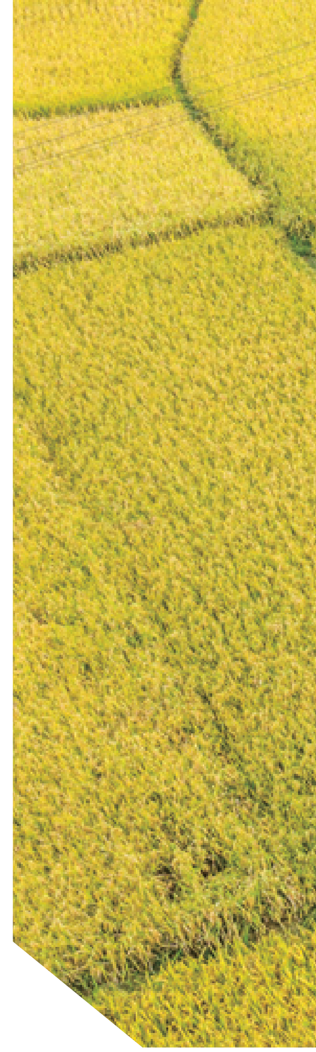
Zhang, L., Xu, H., Li, L., et al. 2019. Comparative Study on CH4Emission from Ratoon Rice and Double-Cropping Rice Fields. Scientia Agricultura Sinica, 52(12), 2101-2113.

Academy of Global Food Economics and Policy (AGFEP), China Academy for Rural Development, Zhejiang University (CARD), Chinese Center for Disease Control and Prevention (CCDC) National Institute for Nutrition and Health (NINH), Centre for lnternational Food and Agricultural Economics, Nanjing Agricultural University (CIFAE), International Food Policy Research Institute(IFPRI), Food and Land Use Coalition (FOLU). 2023. China and Global Food Policy Report. Beijing: Academy of Global Food Economics and Policy.

Academy of Global Food Economics and Policy (AGFEP), China Academy for Rural Development, Zhejiang University (CARD), Centre for lnternational Food and Agricultural Economics, Nanjing Agricultural University (CIFAE), Institute of Agricultural Economics and Development, Chinese Academy of Agricultural Sciences (IAED), International Food Policy Research Institute (IFPRI). 2021. China and Global Food Policy Report. Beijing: Academy of Global Food Economics and Policy.

Chinese Academy of Agricultural Sciences, China Agriculture Green Development Research Society. 2024. China Agricultural Green Development Report 2023. Beijing: Chinese Academy of Agricultural Sciences.
Agricultural and Rural Carbon Peaking and Carbon Neutrality Research Center, Chinese Academy of Agricultural Sciences, Institute of Environment and Sustainable Development in Agriculture, Chinese Academy of Agricultural Sciences, Key Laboratory of Agricultural Environmental Pollution Prevention and Control, Ministry of Agriculture and Rural Affairs. 2024. Report on Low-carbon Agricultural and Rural Development in China (2024).Beijing: Social Sciences Academic Press.
Chinese Nutrition Society. 2021. Scientific Research Report on Dietary Guidelines for Chinese Residents. Beijing: Chinese Nutrition Society.
Zhu, Z., Chen, D., Ye, X. 2024. Current status of standardization development of biochar from straw cabonization and field application. Journal of Zhejiang Agricultural Sciences, 65(07), 1709-1713.

Chapter 2



Options for Methane Mitigation in China's Rice Sector

Jintao Yang[1,2], Yumei Zhang[1,2], Ruizeng Zhang[1,2], Shenggen Fan[1,2], Sheng Zhou[3], Yangyang Li[4], Bin Wang[5], Xiaoguang Yang[4], and Kevin Chen[6,7]

1. Academy of Global Food Economics and Policy, China Agricultural University
2. College of Economics and Management, China Agricultural University
3. Shanghai Academy of Agricultural Sciences
4. College of Resources and Environmental Sciences, China Agricultural University
5. Institute of Environment and Sustainable Development in Agriculture, Chinese Academy of Agricultural Sciences
6. China Academy for Rural Development, Zhejiang University
7. International Food Policy Research Institute

Key Findings

- Methane emissions from rice cultivation in China reached 248 million tonnes of CO_2equivalent (CO_2eq), representing 26.6% of total agricultural greenhouse gas (GHG) emissions in 2021. Model simulations indicate that, due to a declining population and reduced rice consumption, methane emissions could decline by 15.9% in 2035 and by 35.4% in 2060, even without improvements in emission intensity reduction, driven primarily by a reduction in the cultivated area. Nevertheless, methane emissions from paddy fields remain a critical challenge for China in meeting its 2060 carbon neutrality target.
- Simulation results show that by 2035 and 2060, improved water management practices could reduce emissions by 20.4% and 32.4%, respectively; enhanced fertilizer and organic matter management by 10.6% and 16.8%, respectively; use of improved rice varieties by 3.5% and 6.9%, respectively; and optimized cultivation and tillage practices by 4.1% and 8.2%, respectively. A comprehensive mitigation strategy that integrates all of these measures could achieve total emission reductions by 39.1% in 2035 and by 63.8% in 2060.
- Despite the potential, scaling up these technologies faces several challenges. Many are still at the pilot or demonstration stage, with their effectiveness constrained by regional environmental conditions, low adoption rates, and insufficient technical support. Moreover, limited awareness, high technical complexity, and high implementation costs further hinder widespread uptake. Overcoming these barriers requires robust policy support, institutional innovation, and coordinated deployment of integrated technologies to facilitate scalable and sustained adoption.

Policy Recommendations

● Leverage artificial intelligence (AI) to enhance mitigation technologies. To overcome technical barriers, high labor costs, and management inefficiency, China should accelerate the integration of AI-powered solutions, such as smart sensing, real-time data collection, and machine learning, into methane mitigation strategies for rice cultivation. Developing a collaborative "AI + Agriculture" ecosystem could reduce labor intensity, improve efficiency, and support the smart, scalable deployment of emission reduction technologies.

● Accelerate the breeding of low-emission, nutrient-rich rice varieties. Traditional rice breeding programs have long prioritized yield maximization, often at the expense of emissions, nutritional quality, and sustainability. A paradigm shift is needed, from a "yield-first" approach to a "triple optimization" model balancing yield, nutrition, and low emission. Increased R&D funding and targeted policy support for green breeding technologies are essential to establish a low carbon, high quality rice production system.

● Improve adoption rates of methane reduction technologies through institutional innovations. China's fragmented smallholder farming structure hinders the dissemination of low-carbon agricultural technologies. Reforms should promote land consolidation and encourage the transformation of small-scale farms into larger-scale, specialized operations (e.g., family farms, cooperatives). In parallel, governments should expand investments and provide financial incentives such as subsidies and green credit, to support systematic adoption of methane mitigation practices.

2.1 Introduction

As climate change intensifies, methane mitigation has emerged as a critical pathway to achieving global temperature targets. With a global warming potential approximately 28 times that of carbon dioxide, methane is responsible for nearly 30% of global warming (IEA, 2022). Rice cultivation is one of the largest sources of agricultural methane emissions, accounting for 48% of crop-related greenhouse gas emissions globally (Qian et al., 2021).

In response, the international community has introduced several key initiatives. In 2021, the United States and the European Union jointly launched the Global Methane Pledge, aiming to reduce global methane emissions by at least 30% from 2020 level by 2030. The Food and Agriculture Organization of the United Nations (FAO) has continued to advance climate-smart agriculture, promoting practices such as alternate wetting and drying, optimized fertilization, and the adoption of low-methane rice varieties in major rice-producing regions.

China has likewise prioritized methane reduction in agriculture through a series of national policy efforts. These include the Implementation Plan for Emission Reduction and Carbon Sequestration in Agriculture and Rural Areas and the Methane Emission Control Action Plan. In addition, under the U.S.-China Joint Declaration on Climate, the Chinese government has committed to developing a National Methane Action Plan, signaling its sustained commitment to policy leadership and international cooperation.

Methane emissions from China's rice paddies account for approximately 15% to 21% of the global total (FAO, 2025). According to the First Biennial Update Report on Climate Change of the People's Republic of China, methane emissions from rice cultivation in China reached approximately 248 million tonnes of CO_2eq in 2021, representing 26.6% of the country's total agricultural greenhouse gas (GHG) emissions. This positions rice methane reduction as both a priority and a strategic entry point for China's agricultural mitigation efforts.

In recent years, a suite of mitigation technologies such as intermittent irrigation, integrated water and fertilizer management, straw treatment, and the development of high-yield, low-methane rice varieties have been progressively applied, demonstrating promising potential for broader application. However, systematic research remains limited, particularly in assessing mitigation pathways and evaluating economic feasibility. Specifically, comprehensive and comparative analyses of the reduction potential and regional applicability of various technologies remain limited, and the economic assessment of these measures, particularly in terms of cost-benefit quantification and input-output efficiency, remains underdeveloped. Addressing these gaps is crucial for designing targeted methane reduction strategies, achieving national mitigation goals, and supporting China's contribution to global climate commitments.

This report seeks to provide a comprehensive assessment of the current status and spatiotemporal dynamics of methane emissions from rice cultivation in both China and globally. It analyzes emission variations across different production conditions (e.g., climate, soil types, and irrigation regimes) and technological scenarios. Furthermore, it compares the mitigation potential, yield-enhancing effects, and cost-effectiveness of major technologies, evaluates synergies among interventions, and quantifies the emission reduction impacts of both standalone and integrated solutions through simulation modeling.

Based on these analyses, the report identifies optimized pathways that reconcile food security, economic viability, and low-carbon development objectives. The findings aim to inform practical policy design for methane mitigation in China's rice sector and provide evidence-based insights for global efforts in curbing rice-related methane emissions.

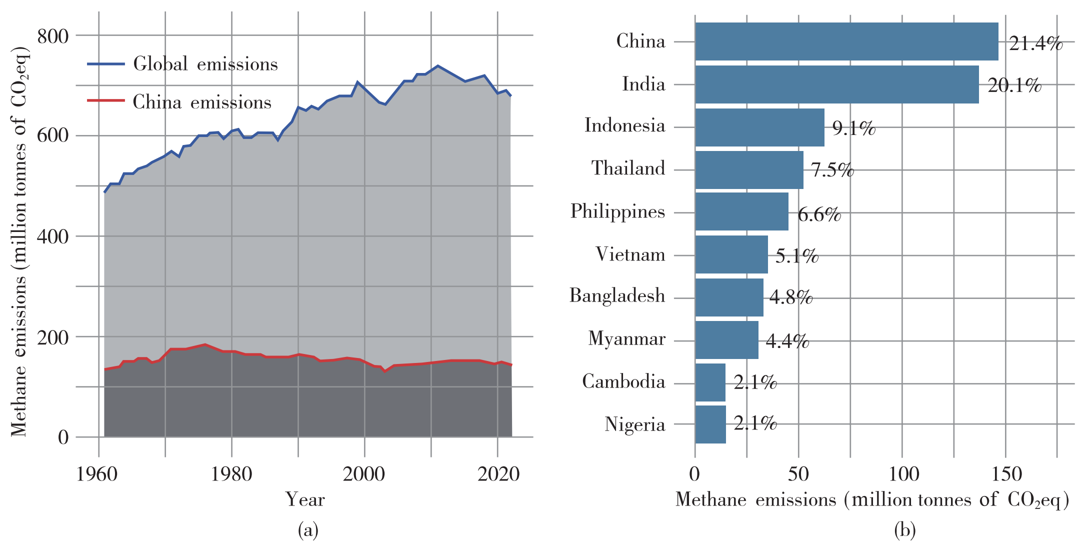
2.2 Trends in Methane Emissions from Rice Cultivation

2.2.1 Regional Characteristics of Rice Methane Emissions in China and Globally

According to estimates from FAO based on the IPCC Tier 1 methodology (FAO, 2025), methane emissions from rice paddies exhibit pronounced regional disparities and distinct temporal trends (Figure 2-1a). Between 1961 and 2022, the global harvested area of rice expanded from 115 million hectares to 165 million hectares, driving an increase in methane emissions from 488 million tonnes of CO_2eq to 683 million tonnes of CO_2eq. Three core production regions, East Asia, South Asia, and Southeast Asia, together accounted for more than 80% of global methane emissions from rice paddies. In contrast, rice-growing areas in Africa, South America, Europe, and North America, primarily located in belt-shaped agroecological regions, collectively contributed less than 20% of global emissions.

Developed countries, owing to their limited paddy area, have maintained relatively stable methane emission levels over time, contributing approximately 4% to the global total annually. Meanwhile, developing countries have experienced accelerated emission growth, largely driven by the expansion of rice cultivation to meet the demands of growing populations. In 2022, the top six rice-producing countries by total methane emissions were China, India, Indonesia, Thailand, the Philippines, and Vietnam, accounting for 21.4%, 20.1%, 9.1%, 7.5%, 6.6%, and 5.1% of global emissions, respectively (Figure 2-1b).

Figure 2-1 Global Trends in Methane Emissions from Paddy Fields. (a) Historical trends in global and China's methane emissions from rice cultivation, 1960-2022. (b) Country-level contributions to global paddy methane emissions in 2022.



Data source: FAO Database

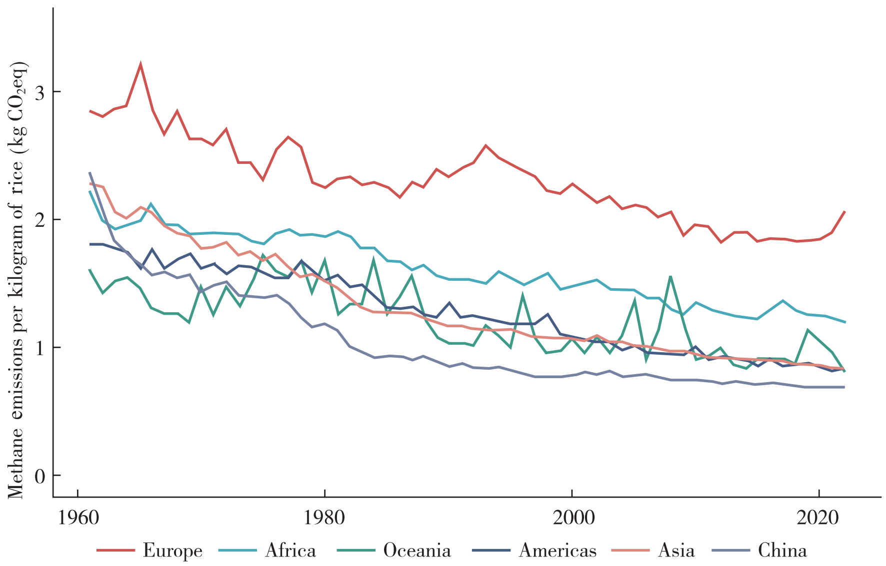
At the global level, methane emission intensity from rice cultivation has shown a significant downward trend over time (Figure 2-2), declining from approximately 2.3 kg CO_2eq per kilogram of rice in 1961 to 0.9 kg in 2022 (FAO, 2025). This reduction reflects considerable progress in greenhouse gas mitigation achieved in global rice production over the past six decades, with the most substantial declines occurring between the 1960s and 1970s. The emission reduction achievements during this period are closely linked to the agricultural Green Revolution, which brought about widespread adoption of mechanization, optimization of cropping systems, improved irrigation management, and enhanced fertilizer use efficiency. However, over the past decade, the decline in global methane emission intensity from rice cultivation has noticeably plateaued (Xu et al., 2024), suggesting diminishing marginal returns from conventional mitigation strategies. This trend underscores the urgent need for more systematic technological innovation and robust policy incentives to unlock the next phase of emission reductions. It also highlights the limitations of relying solely on traditional approaches and underscores the importance of integrated, transformative solutions supported by robust policy frameworks to drive continued progress in methane mitigation from rice production systems.

Methane emission intensity of rice cultivation varies significantly across regions. According to 2022 data, Europe recorded the highest emission intensity at 2.1 kg CO_2eq per kilogram of rice, followed by Africa at 1.2 kg. In contrast, Asia, the Americas, and Oceania reported comparatively lower levels, all around 0.8 kg. China stands out with one of the lowest emission intensity globally, at approximately 0.7 kg CO_2eq per kilogram of rice.

These regional disparities reflect variations in cultivation systems, hydrological conditions, soil characteristics, climate regimes, and field management practices, which are also closely correlated with rice yield levels. For example, China has achieved a sustained decline in paddy methane emission intensity alongside increasing yields, facilitated by the adoption of advanced cultivation techniques and optimized irrigation practices. This illustrates the potential for sustainable intensification in rice systems, enhancing productivity while simultaneously reducing environmental impacts.

The global patterns suggest that modernization and technological advancement can effectively decouple yield growth from emission increases. However, persistently high emission intensities in certain regions highlight the continued need for targeted technical support and knowledge transfer to promote best practices. China's experience in achieving low emission intensity while ensuring food security provides valuable insights for other rice-producing countries aiming to harmonize agricultural development with climate objectives.

Figure 2-2 Regional Characteristics of Methane Emission Intensity from Rice Cultivation (1961–2022)



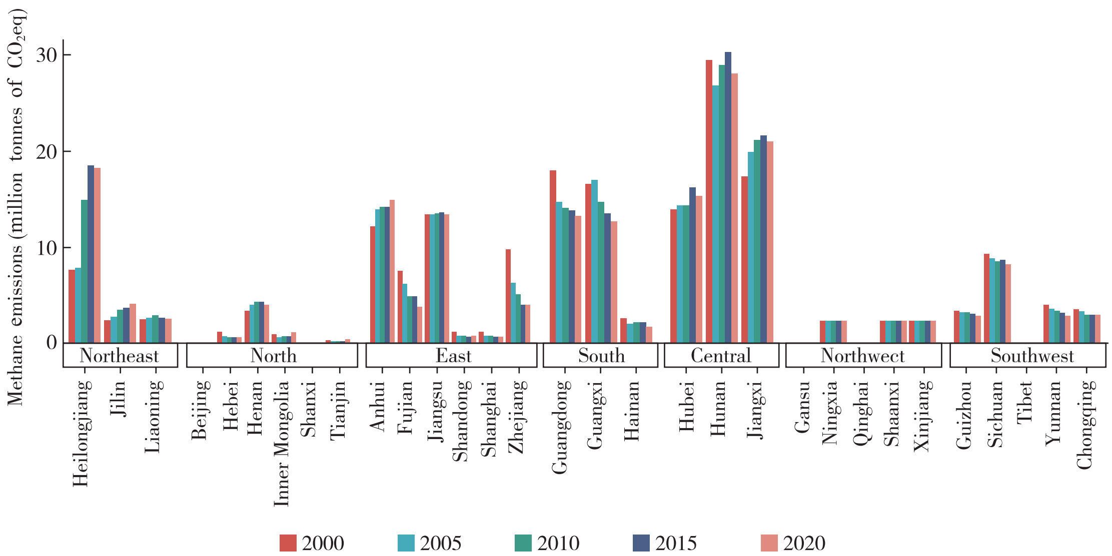
Data source: FAO Database

2.2.2 Regional Characteristics of Methane Emissions from Rice Cultivation in China

In recent years, China's rice production has continued to grow steadily, while total methane emissions have remained relatively stable. According to the First Biennial Update Report on Climate Change of the People's Republic of China, methane emissions from rice cultivation reached approximately 248 million tonnes of CO_2eq in 2021. Due to the vast geographic distribution of rice-growing regions across diverse ecological zones, distinct cultivation practices have emerged—each shaped by variations in farming scale, irrigation methods, rice variety selection, and cropping systems (Yang et al., 2025). These factors have led to pronounced spatial disparities in methane emissions across regions (Figure 2-3).

For instance, Hunan, Jiangxi, and Hubei provinces reported methane emissions of 27.9, 13.2, and 13.3 million tonnes of CO_2eq, respectively—forming typical 'high-yield, high-emission' zones. By contrast, rice-producing regions in northern China generally exhibit both lower total methane emissions and reduced emission intensities.

Figure 2-3 Methane Emissions from Rice Paddies by Region in China (2000–2020)



Data source: Shen et al. (2024)

From a natural resource and climatic perspective, rice areas in southern China are predominantly located in warm, humid subtropical or tropical zones, where elevated temperatures and abundant precipitation foster intensified soil microbial activity, thereby enhancing methane generation. In contrast, northern regions fall within cold-temperate zones, where extended winter soil freezing effectively suppresses microbial activity, limiting methane production. For example, although Heilongjiang Province ranked first in national rice output in 2020 (29.1 million tonnes), it recorded methane emissions of only 18.2 million tonnes of CO_2eq, third nationally, due to climatic constraints on microbial methane formation.

Furthermore, double-cropping rice systems are widely practiced in southern China, where early rice typically matures in approximately 100-120 days and late rice in 110-130 days. This sequential cultivation extends the duration of anaerobic, waterlogged conditions in paddy fields, intensifying methane emissions. In contrast, northern regions primarily adopt single-cropping systems. Although the individual crop growth period is longer (140-160 days) the cumulative flooding duration is considerably shorter, leading to lower overall methane emissions relative to the south.

From a field management perspective, southern provinces such as Hunan and Jiangxi, benefiting from ample precipitation, commonly employ continuous flooding irrigation practices. This approach maintains prolonged anaerobic soil conditions, which are highly conducive to methane generation. In contrast, rice-growing regions in northern China, constrained by limited water resources, have increasingly adopted intermittent or controlled irrigation techniques, thereby reducing the duration and intensity of anaerobic soil conditions and help curb methane emissions.

These regional divergences in methane emission intensity underscore the dual influence of natural climatic conditions and agronomic management practices in shaping emission outcomes. Integrating climate-resilient farming systems with optimized water management strategies presents a critical opportunity to mitigate methane emissions effectively while maintaining, or even enhancing agricultural productivity.

2.3 Rice Paddy Methane Mitigation Technologies and Cost-Benefit Analysis

2.3.1 Analysis of Factors Influencing Methane Emissions from Rice Paddies

Methane emissions from rice paddies are primarily governed by soil characteristics, water management practices, climatic conditions, and agronomic techniques (Tang et al., 2022).

First, soil characteristics play a fundamental role in methane generation dynamics. Paddy soils represent complex anaerobic ecosystems, where methane production and transport are shaped by variables such as water retention capacity, organic matter content, pH, and temperature. In general, soils with lower water content and higher permeability inhibit methanogenic activity, thereby suppressing methane emissions. Organic matter content exhibits a strong positive correlation with methane production. Meanwhile, both highly acidic and highly alkaline soils can suppress methanogen activity. Regions such as the Yangtze River Plain, the southeastern coastal zones, low-lying southern regions, and marshland areas in the Northeast Plain are particularly prone to high methane emissions due to their poor aeration and high organic matter accumulation (Xie et al., 2014).

Second, water management is a critical determinant of methane emissions from paddy fields. Conventional continuous flooding creates prolonged anaerobic conditions that facilitate methanogenesis while simultaneously reducing water use efficiency. Although China has gradually transitioned from traditional continuous flooding to mid-season drainage practices, water management remains inefficient, especially in the southern rice-growing regions, where extended crop cycles sustain anaerobic conditions and contribute to persistently high methane emissions.

Thirdly, climatic factors, especially accumulated temperature and precipitation, strongly influence methane emissions. Accumulated temperature directly affects the rice growth cycle: higher accumulated temperatures typically shorten the growth duration, while lower accumulated temperatures prolong the crop cycle and extend the duration of field flooding, thereby increasing methane emissions. Temperature also modulates the activity levels of methanogenic archaea and methane-oxidizing bacteria in the soil. In regions with higher accumulated temperatures, frequent irrigation may prolong anaerobic conditions, further driving methane emissions. (Wang et al., 2017). Precipitation, particularly during the tillering and milk-ripe stages, can intensify flooding, increasing emissions during these peak periods.

Finally, agronomic practices significantly affect methane emissions from rice paddies. Improper fertilization, inappropriate straw incorporation, and excessive tillage operations can all contribute to elevated emissions. The misapplication of organic fertilizers and the return of straw to the field increase the availability of substrates for methanogens, while also reducing the redox potential (Eh) of flooded soils-conditions that are highly conducive to methane production. Excessive tillage disrupts soil structure and accelerates organic matter decomposition, further exacerbates emissions.

2.3.2 Methane Mitigation Measures in Rice Paddies

Mitigation strategies can be grouped into four categories: water management; fertilization and organic material management; varietal innovation and management; and cultivation management. These measures vary in their effectiveness, cost-efficiency, and regional applicability. A summary of the mitigation performance of each strategy is provided below.

Water Management. Water-saving irrigation techniques, such as alternate wetting and drying (AWD), thin-shallow-wet-dry irrigation, and controlled irrigation, significantly improve soil aeration relative to traditional continuous flooding (e.g., mid-season drainage), thereby enhancing methane oxidation by altering anaerobic soil conditions (Tang et al., 2022). These approaches can reduce methane emissions by 22.7% to 67% (Li et al., 2020, 2024), while simultaneously increasing rice yields by 1.4% to 6.7%. Specifically, thin-shallow-wet-dry irrigation reduces methane production by shortening the flooding period (Ma et al., 2021), achieving emission reductions of 9.6% to 51.6% (Li et al., 2020; Dong et al., 2017). This method also promotes tillering and increases the number of productive tillers, thereby enhancing yield by 2.2% to 5%. Controlled irrigation adjusts water supply based on the crop's physiological water demands at various growth stages and leverages the rice plant's self-regulation capacity (Peng et al., 2012). By delaying irrigation and modifying soil redox potential, it facilitates methane oxidation (Wang et al., 2017). This method achieves methane emission reductions of 28.3% to 82.8% (Hou et al., 2016; Huang et al., 2022), improves grain yields by 0.2% to 8%, and enhances grain quality, including protein content and milling rate.

Fertilization and Organic Material Management. Multiple fertilization strategies can mitigate methane emissions from rice paddies through diverse mechanisms. These include the application of slow-release or stabilized fertilizers, composted organic fertilizers, urea amended with viable microbial agents, straw composting and return, strip mulching, and biochar incorporation. slow-release or stabilized fertilizers align nitrogen availability with crop growth demands, thereby enhancing nitrogen use efficiency. These fertilizers can reduce methane emissions by 11.9%-65% (Wang et al., 2016; Yin et al., 2016) and increase yields by 4.8%-13.3%. Composted organic fertilizers-due to the pre-decomposition of most organic matter-can lower methane emissions by 23.6%-75.6% (Qian et al., 2022; Chen et al., 2011). The use of urea amended with viable microbial agents that inhibit methanogenic activity can reduce emissions by 24%-42.5% (Wang et al., 2016), while boosting yields by 1.4%-4.3%. Straw composting mirrors the emission reduction mechanism of organic composting, achieving 34%-72% reductions compared to fresh straw incorporation. Straw return methods also significantly influence emissions: uniform incorporation tends to increase methane release, whereas strip mulching can reduce emissions by 21%-32% and enhance yields by 0.5%-2.8%. Biochar improves soil aeration through its porous structure and supports methane oxidation by elevating soil pH and enhancing methanotroph activity, while suppressing methanogen proliferation (Sun et al., 2024). Optimal application rates of 15-25 t/ha have been shown to reduce methane emissions by 31.2%-50% and increase yields by 5.8%-31.9% (Li et al., 2023).

Varietal Innovation and Management. High-yield, low-methane rice varieties, water-saving, drought-resistant varieties, and perennial rice varieties have emerged as promising pathways to reconcile the dual objectives of productivity enhancement and methane mitigation. Studies show that under conditions of high soil organic matter content (>2.1%), rice varieties with a high harvest index and well-developed aerenchyma tissues exhibit notable synergies between yield increase and emission reduction (Tang et al., 2022), highlighting the strategic importance of identifying and scaling such varieties. Representative high-yield, low-methane varieties such as Huanghuazhan, Jinyou 402, Yongyou 9, and Yuexinzhan have demonstrated methane emission reductions of 14.9%-64.5% compared to conventional varieties, while achieving yield gains of 4.6%-27.6% (Fu et al., 2012; Sun et al., 2015). Similarly, water-saving, drought-resistant varieties, including Hanyou 73, Hanyou 2, Hanyou 3, Qinhanyou 651, and Hanyou 718-mitigate methane emissions by shortening flooding durations, optimizing irrigation patterns, enhancing root oxygen secretion, reducing root exudates, and improving nitrogen use efficiency. These varieties exhibit superior drought tolerance through greater root biomass, larger active absorption areas, and extended root length, enabling higher soil water uptake efficiency and photosynthetic performance. Yield improvements over conventional varieties range from 1.6% to 10.1% (Li et al., 2022; Zhang et al., 2023). Recent advancements in both low-methane high-yield varieties and the adoption of dry direct-seeding cultivation systems have revitalized China's efforts toward green, low-carbon rice production. Notably, the development of perennial rice, such as Perennial 23 and Yunda 25, represents a breakthrough in climate smart rice agriculture. These cultivars regenerate from rhizomes after harvest and feature robust root systems with strong oxygen secretion capacity, which enhances soil oxygenation and inhibits methanogen activity. They have demonstrated emission reductions of 21.7%-25.9% (Xu et al., 2025) while maintaining yields comparable to traditional varieties. In addition to their methane mitigation benefits, perennial rice varieties also contribute to long-term soil health and resource efficiency, offering a resilient and sustainable approach to rice cultivation that aligns with food security and climate objectives.

Cultivation and cropping management practices, including no-tillage, direct seeding, film mulching, and water-fertilizer coupling, offer considerable potential for reducing methane emissions from rice production systems. No-tillage reduces soil disturbance and maintains a more stable soil redox potential (Eh), which inhibits methanogenic bacterial activity. This practice has been shown to reduce methane emissions by 5.7%-69.1%. However, it may also increase the incidence of pests and diseases, thereby raising control costs. Direct seeding avoids the soil disruption associated with traditional transplanting, improves soil aeration, and enhances Eh conditions, contributing to methane reductions of 15.7%-76.1%. Nevertheless, this method may affect dry matter accumulation, nutrient availability, weed control, and lodging resistance, leading to yield variations ranging from -5.2% to +1.9%. Film mulching substantially curbs methane emissions (43.5%-95%) by optimizing soil moisture, microbial communities, and temperature conditions. Yet, its impact on yield remains contested in existing literature. Water-fertilizer coupling aligns water and nutrient supply with rice physiological needs across growth stages, improving both soil aeration and fertility. This integrated approach achieves methane emission reductions of 46.5%-62.7%, while also boosting yields by 6.9%-14.1%. In addition, innovative cropping systems, such as ratoon rice and perennial rice, represent promising frontiers for advancing China's low-carbon rice transformation. These systems offer opportunities to optimize resource use efficiency and reduce greenhouse gas emissions, providing viable models for sustainable intensification in the rice sector.

Table 2-1 Methane Mitigation Technologies and their Effects on Rice Paddies

	Technologies	Comparator	Emission Change Rate per Unit Area (%)	Yield Change Rate (%)
Water management	Alternate Wetting and Drying (AWD)	Conventional Irrigation (Mid-season Drainage)	22.7~67	1.4~6.7
	Thin-Shallow-Wet-Drying Irrigation (TSWDI)	Conventional Irrigation (Mid-season Drainage)	9.6~51.6	2.2~5
	Controlled Irrigation	Conventional Irrigation (Mid-season Drainage)	28.3~82.8	0.2~8
Fertilizer and organic matter management	Application of Slow-Release or Stabilized Fertilizers	Application of Conventional Nitrogen Fertilizer	11.9~65	4.8~13.3
	Application of Composted Organic Fertilizers	Application of Fresh Organic Fertilizers	23.6~75.6	-2.5~7
	Application of Urea Amended with Viable Microbial Agents	Application of Conventional Nitrogen Fertilizer	24~42.5	1.4~4.3
	Accelerated Decomposition and Incorporation of Crop Straw	Incorporation of Fresh Crop Straw	34~72	-1.7~4.7
	Strip Mulching and Soil Incorporation of Crop Straw	Straw and Soil Mixing Return to the Field	21~32	0.5~2.8
	Biochar Application	Without Biochar Application	31.2~50	5.8~31.9
Varietal innovation and management	Adoption of High-Yield, Low-Emission Varieties	Adoption of Conventional Varieties	14.9~64.5	4.6~27.6
	Adoption of Water-Saving, Drought-Resistant Varieties	Adoption of Conventional Varieties	3.7~71.7	1.6~10.1
	Adoption of Perennial Rice Varieties	Adoption of Conventional Varieties	21.7~25.9	1.5~2.7
Cultivation and cropping management	No-Tillage	Conventional Tillage	5.7~69.1	-5.8~5.3
	Direct Seeding	Seedling Transplanting	15.7~76.1	-5.2~1.9
	Film Mulching	Non-Mulching	43.5~95	-2.4~8.7
	Water-Fertilizer Coupling	Conventional Water and Nitrogen Management	46.5~62.7	6.9~14.1

Box 2.1 Case Study of Innovative Rice Varieties in China

Breakthrough in High-Yield, Low-Methane Rice Varieties

The fumarate content in rice root exudates plays a key role in regulating methane emissions from paddy fields. A novel rice variety, developed through the hybridization of high-yield and low-methane-emitting cultivars, achieves a dual optimization of emission mitigation and yield enhancement via root exudate regulation mechanisms. This variety demonstrates a distinctive root secretion profile, characterized by a significant reduction in fumarate exudation and a corresponding increase in ethanol secretion. This biochemical modulation reduces field methane emissions by an average of 70% compared to conventional varieties. Concurrently, the variety achieves exceptional productivity, yielding 9 tonnes per hectare-a figure 90.2% higher than the global average rice yield in 2024 (Jin et al., 2025). Currently undergoing varietal registration, its full agronomic package includes the application of fumarate synthesis inhibitors within fertilizer systems to further enhance methane mitigation. This innovation represents a critical breakthrough for aligning rice production with carbon neutrality goals, offering a genetic foundation for the development of high-yield, low-carbon agricultural systems.

Source: https://www.sciencedirect.com/science/article/abs/pii/S1674205225000292

Water-Saving, Drought-Resistant Rice Varieties under Dry-Seeding and Dry-Management Practices

Water-saving, drought-resistant (WDR) rice varieties represent a transformative innovation that integrates the high yield and grain quality of traditional irrigated rice with the stress-resilience traits of upland rice. These varieties are well-suited to simplified cultivation modes, including dry-seeding with dry-management, dry-seeding with wet-management, wet-seeding with wet-management, and mechanized dry-seeding. Under drought conditions, WDR varieties exhibit elevated levels of peroxidase and superoxide dismutase, enhancing their ability to neutralize reactive oxygen species. Additionally, increased concentrations of zeatin, zeatin riboside, and tissue-bound water improve drought tolerance and facilitate rapid recovery upon rehydration. These physiological traits allow WDR varieties to maintain stable yields even in marginal fields with poor irrigation conditions. Under conventional irrigated settings, they can reduce water consumption by more than 50%, easing water stress and lowering agricultural production costs. When combined with dry direct-seeding and dry-management practices, methane emissions can be reduced by 70% to 90% (Sun Huifeng et al., 2020; Zhang et al., 2021).

Since the successful development of the first WDR variety, over 20 million mu (~1.3 million hectares) have been cumulatively planted across provinces such as Anhui, Hubei, Hunan, Jiangxi, Guangxi, and parts of Northeast China. The annual planting area now exceeds 5 million mu (~333,000 hectares) and continues to expand. Given that approximately 70% of China's rice production area consists of middle- to low-yield fields, even partial adoption of WDR varieties with dry-seeding dry-management techniques could increase total coverage to more than 10% within the next 10 to 15 years.

Source: https://sagc.org.cn/kjcb/kjfw/content_4106

Box 2.2 Case Studies of Low-carbon Rice Cultivation in China

Low-carbon Advantages of Ratoon Rice Cultivation

Ratoon rice cultivation leverages the regenerative capacity of residual stalks from the first-season harvest to produce a second crop. This system offers multiple advantages, including yield enhancement, labor and seed savings, and reduced use of fertilizers and pesticides, thereby improving land use efficiency and cropping intensity. The low-carbon benefits of ratoon rice stem primarily from the elimination of second-season sowing, nursery raising, and transplanting, which significantly reduces the operation time and fuel consumption of agricultural machinery, leading to lower associated carbon emissions. Moreover, relying on the regrowth of existing stalks, the system reduces both the frequency and amount of fertilizer application, thereby lowering emissions from fertilizer production and application. Additionally, ratoon rice cultivation shortens the duration of field flooding, cutting methane emissions by approximately 43.5% (Zhou Haozhi et al., 2023). China's potential ratoon rice planting area exceeds 50 million mu (~3.3 million hectares), with additional yield reaching about 300 kg per mu, contributing a national incremental output of approximately 15 billion kilograms. Between 2000 and 2020, the cumulative ratoon rice planting area reached 63.6 million mu (~4.2 million hectares), with demonstration sites maintaining yields above 1,336.8 kg per mu for 22 consecutive years, peaking at 1,449.7 kg per mu. From 2018 to 2020 alone, ratoon rice expanded across 12.9 million mu (~858,600 hectares), increasing rice output by 378 million kilograms, generating RMB 944 million in direct economic benefits, and achieving total cost savings and efficiency gains of RMB 1.9 billion. These figures highlight the significant economic, social, and ecological value of ratoon rice cultivation.

Source: https://www.faas.cn/cms/html/fjsnykxy/2023-06-26/543089554.html

Emission Reduction Features and Advantages of Perennial Rice

Traditional rice systems face increasing constraints including repetitive labor, soil erosion, and high production costs, while food security challenges intensify amid population growth and shrinking arable land. Since 1997, a research team led by Hu Fengyi at Yunnan University has pursued the development of perennial rice-transforming annual rice into perennial cultivars-to reduce labor intensity, lower production costs, and strengthen long-term food security. Perennial rice propagates through underground stems and is capable of multiple harvests over 3 to 5 years without replanting, under no-tillage management systems. It contributes to methane reduction through multiple mechanisms: Extensive root systems enhance soil structure and oxygen availability, reducing anaerobic conditions that promote methane generation. No-tillage practices minimize soil disturbance, suppressing methanogen activity. The stabilized microbial communities in perennial paddy systems improve the soil's methane oxidation capacity, further curbing emissions (Zhang et al., 2023). In 2018, 'Perennial Rice 23' became the first commercially approved perennial cereal crop globally. Since then, additional varieties such as Yunda 25 and Yunda 107 have been developed and successfully piloted in China and neighboring countries, marking a major advancement in the shift toward low-carbon, sustainable rice cultivation.

Source: https://yn.yunnan.cn/system/2022/11/08/032343321.shtml

2.3.3 Cost-Benefit Analysis of Rice Paddy Methane Mitigation

While the aforementioned methane mitigation technologies have demonstrated varying degrees of effectiveness, their practical deployment necessitates careful evaluation of economic costs and benefits. To support comprehensive assessment and policy decision making, we systematically compiled and analyzed the cost-benefit characteristics of each mitigation measure (Table 2-2).

Table 2-2 Cost-Benefit Analysis of Methane Mitigation Pathways in Rice Paddies

	Technical Name	Change in Cost (CNY/hectare)	Change in Benefit (CNY/hectare)	Net Benefit (CNY/hectare)
Water management	Alternate Wetting and Drying (AWD)	1084	563	-521
	Thin-Shallow-Wet-Drying Irrigation (TSWDI)	1140	990	-150
	Controlled Irrigation	1161	1084	-77
Fertilizer and organic matter management	Application of Slow-Release or Stabilized Fertilizers	-468	1414	1882
	Application of Composted Organic Fertilizers	1000	-398	-1398
	Application of Urea Amended with Viable Microbial Agents	100	579	479
	Accelerated Decomposition and Incorporation of Crop Straw	200	581	381
	Strip Mulching and Soil Incorporation of Crop Straw	-525	464	989
	Biochar Application	7190	1541	-5649
Varietal innovation and management	Adoption of High-Yield, Low-Emission Varieties	-810	1824	2634
	Adoption of Water-Saving, Drought-Resistant Varieties	-485	1040	1525
	Adoption of Perennial Rice Varieties	-3440	300	3740

	Technical Name	Change in Cost (CNY/hectare)	Change in Benefit (CNY/hectare)	Net Benefit (CNY/hectare)
Cultivation and cropping management	No-Tillage	-2216	-163	2053
	Direct Seeding	450	-1102	-1552
	Film Mulching	3313	720	-2593
	Water-Fertilizer Coupling	247	2968	2721

● Water Management

Compared to traditional irrigation practices, water-saving irrigation methods, such as alternate wetting and drying (AWD), thin-shallow-wet-drying irrigation, and controlled irrigation, require more frequent field interventions, leading to increased labor demands, higher machinery operation costs, and altered irrigation expenses. According to recent literature, these three approaches collectively increase labor input by approximately 10 additional workdays per hectare and raise machinery operation costs by around 300 CNY per hectare relative to conventional mid-season drainage irrigation (Tang et al., 2022). However, they also offer significant water-saving benefits, reducing irrigation water usage by approximately 30% (AWD), 18% (shallow-wet-drying), and 15% (controlled irrigation), respectively (Gao et al., 2024), thereby lowering associated irrigation costs. Based on estimates accounting for both drainage and re-watering operations, the irrigation cost for conventional rice cultivation is approximately 450 CNY/hectare. When integrating the costs of labor, machinery, and adjusted irrigation fees, the total additional cost per hectare for implementing the respective water-saving methods is: 1,084 CNY/hectare for alternate wetting and drying, 1,140 CNY/hectare for shallow-wet-drying irrigation, and 1,161 CNY/hectare for controlled irrigation. Despite these cost increases, these technologies also boost rice yields, partially offsetting the additional expenses. After factoring in the incremental yield benefits, the estimated net profits per hectare relative to traditional practices are: -521 CNY/hectare for alternate wetting and drying, -150 CNY/hectare for shallow-wet-drying irrigation, and -77 CNY/hectare for controlled irrigation.

● Fertilization and Organic Material Management

Slow-release or stabilized fertilizers (e.g., sulfur-coated compound fertilizers) are approximately 50% more expensive than conventional options, yet they reduce application frequency and streamline operations, significantly lowering labor costs. While the additional fertilizer cost is about 315 CNY/ha, yield increases by 550 kg/ha, and reduced application frequency lowers labor costs by 468 CNY/ha, resulting in a net profit of 1,882 CNY/ha. For composted organic fertilizers, the composting process requires microbial inoculants and personnel for turning, fermentation, crushing, and screening, generating additional expenses in materials, labor, and machinery. The total cost increase is estimated at 1,000 CNY/ha compared to fresh application, while yield revenue declines by 398 CNY/ha, resulting in a net loss of 1,398 CNY/ha. The addition of microbial inoculants to fertilizers costs around 100 CNY/ha but generates 579 CNY/ha in extra yield revenue, yielding a net gain of 479 CNY/ha. Straw return methods also influence machinery costs: composted return increases costs by 200 CNY/ha, while strip mulching reduces them by 525 CNY/ha. Biochar, priced at around 1,700 CNY/ton, is typically applied at 20 tons/ha every five years, resulting in an average cost of 6,800 CNY/ha plus 390 CNY/ha in machinery operation. Despite boosting yield value by 1,541 CNY/ha, this leads to a net cost increase of 5,649 CNY/ha. This analysis reveals the complex economic trade-offs among fertilization strategies: while some advanced approaches offer favorable returns, others entail substantial upfront costs, underscoring the need for targeted policy support or long-term investment frameworks. Regional differences in labor, equipment, and market prices must also be factored in to determine optimal implementation pathways.

● Varietal Innovation and Management

High-yield, low-methane and water-saving drought-resistant rice varieties generally incur higher seed costs than conventional cultivars. For instance, Huanghuazhan and Hanyou 73 require additional seed investments of CNY 810 and CNY 640 per hectare, respectively.

However, Hanyou 73 reduces irrigation and drainage expenses by CNY 1,125/ha (Du et al., 2022). Considering yield gains, the estimated net economic benefits for these varieties are CNY 2,634/ha and CNY 1,525/ha, respectively. For perennial rice varieties such as Perennial 23, cost savings mainly from reduced labor can reach CNY 3,440/ha, along with an additional CNY 300/ha in yield revenue, resulting in a total net benefit of CNY 3,740/ha.

● Cultivation and Cropping Management

No-till rice cultivation eliminates mechanical operations such as plowing and rotary tillage, thereby reducing machinery and labor costs; however, it may increase pest pressure and pesticide use. According to the literature, no-till systems generate total cost savings of approximately CNY 2,216 per hectare, translating into a net profit of CNY 2,053 per hectare after accounting for yield variations. Direct seeding eliminates the need for nursery and transplanting operations, reducing machinery costs by about CNY 300 per hectare. However, the lack of early-stage weed control increases pesticide expenditures, and yield reductions result in a net revenue loss of CNY 1,102 per hectare-leading to an overall net loss of CNY 1,552 per hectare. Plastic film mulching, though agronomically beneficial in some contexts, incurs substantial input costs, including film materials, labor, and machinery, amounting to an additional CNY 3,313 per hectare. Even when considering yield gains, this practice results in a negative net return of CNY 2,593 per hectare. Water-fertilizer coupling, while requiring higher labor and equipment maintenance, offsets these costs through reduced fertilizer and irrigation inputs. With a modest additional cost of CNY 247 per hectare, this approach yields a net profit of CNY 2,721 per hectare due to significant productivity gains. This comparative assessment highlights distinct trade-offs among cultivation practices: low-input systems like no-till offer clear economic advantages, while input-intensive technologies such as plastic mulching face constraints in financial viability. Water-fertilizer coupling stands out as a cost-effective, productivity enhancing innovation.

Overall, varietal innovation and management represent the most economically viable strategy, simultaneously achieving yield gains and emission reductions at comparatively low costs. In contrast, water management practices, despite their substantial mitigation potential, tend to be economically unattractive under current conditions, with all evaluated scenarios resulting in negative net returns. Among fertilization and organic material management options, controlled-release or stabilized fertilizers, effective microbial inoculants, decomposed straw return, and strip mulching offer favorable cost-benefit profiles. Conversely, the application of biochar and composted organic manure entails high input costs, undermining their economic feasibility. Within cultivation and cropping management, no-till farming and water-fertilizer coupling emerge as cost-effective approaches, delivering both environmental and productivity benefits. By comparison, direct seeding and film mulching perform less favorably due to increased input costs or potential yield trade-offs.

2.4 Simulation of Methane Mitigation Scenarios in Paddy Fields

Building on a comprehensive evaluation of methane mitigation technologies and their impacts on yield and emissions, this study utilizes the China Agricultural University Agrifood System Model (CAU-AFS Model) to simulate future trajectories in rice production, mitigation potential, and net economic returns under alternative methane reduction scenarios for China's rice sector.

2.4.1 Scenario Design

To evaluate the long-term implications of methane mitigation strategies in China's rice sector, this study constructs one baseline scenario, five single-measure mitigation scenarios, and one integrated mitigation scenario. The baseline scenario uses 2021 as the reference year and applies a recursive dynamic modeling approach to project rice production and consumption trends through 2060 under a business-as-usual (BAU) trajectory. It incorporates key macroeconomic and demographic drivers, including population decline, economic growth, and yield improvements due to technological progress, while assuming that methane emission intensity per unit area remains constant over time.

The five mitigation scenarios represent distinct technical pathways for reducing methane emissions and enhancing productivity. Each scenario simulates the impacts of a specific intervention, with parameter assumptions derived from a synthesis of empirical studies. To account for uncertainties, each scenario includes low-, medium-, and high-intensity implementation assumptions; for conciseness, only the medium-intensity parameters are detailed below:

Productivity Enhancement Scenario (SRPROD): Assumes increased investment in agricultural R&D and technology extension services. Enhanced productivity reduces methane emission intensity without raising input levels. Yields are projected to increase by 5% by 2035 and 10% by 2060.

Water Management Scenario (SRWAT): Promotes practices such as alternate wetting and drying, shallow intermittent irrigation, and controlled irrigation scheduling. These methods improve soil aeration and stimulate methanotrophic microbial activity. Methane emissions are assumed to decline by 40%, with yields rising by 3%. Adoption rates are projected to reach 50% by 2035 and 80% by 2060.

Fertilizer and Organic Input Management Scenario (SRFET): Incorporates the use of slow- or controlled-release fertilizers, composted organic matter, microbial inoculants, and biochar. Emissions are expected to decrease by 25%, while yields increase by 4%. Adoption rates reach 50% by 2035 and 80% by 2060.

Varietal Innovation and Management Scenario (SRVAR): Focuses on scaling up the adoption of high-yield, low-emission rice varieties and drought-tolerant, water-efficient varieties. This pathway assumes a 15% reduction in methane emissions and a 7% increase in yield, with adoption expanding to 20% by 2035 and 40% by 2060.

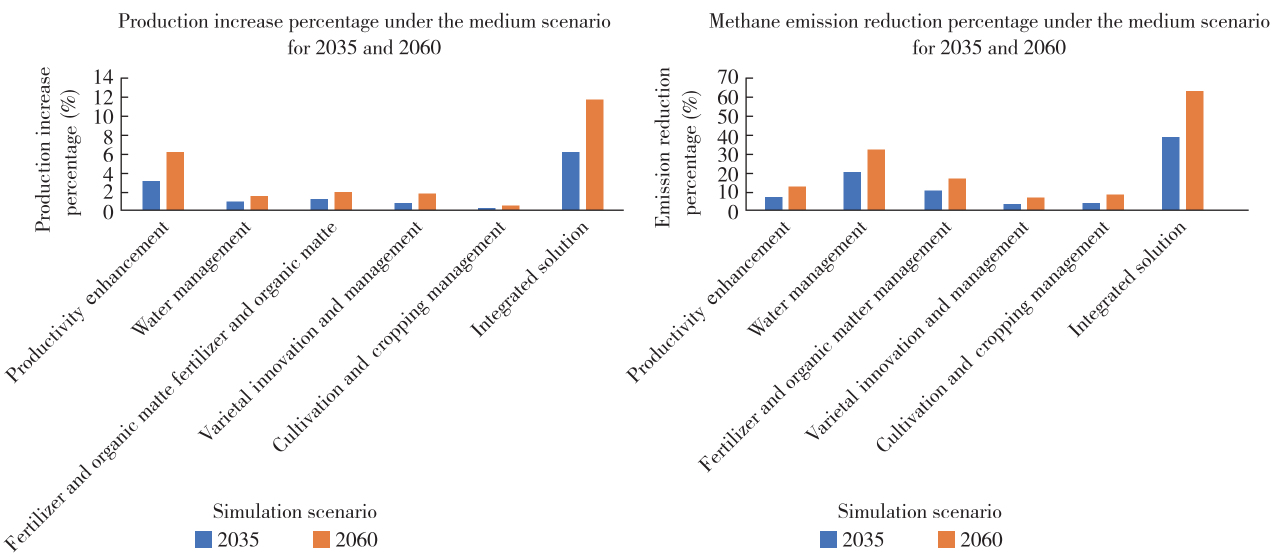
Cultivation and Cropping Management Scenario (SRCUL): Encompasses techniques such as no-tillage, direct seeding, and film mulching. These practices are assumed to reduce methane emissions by 30% and increase yields by 2%, with adoption rates of 20% by 2035 and 40% by 2060.

Integrated Mitigation Scenario (SRICE): Recognizing the limitations and synergies among individual measures, this comprehensive scenario combines all five mitigation strategies to assess their cumulative impacts on emission reduction and yield performance under a unified implementation framework.

2.4.2 Simulation Results

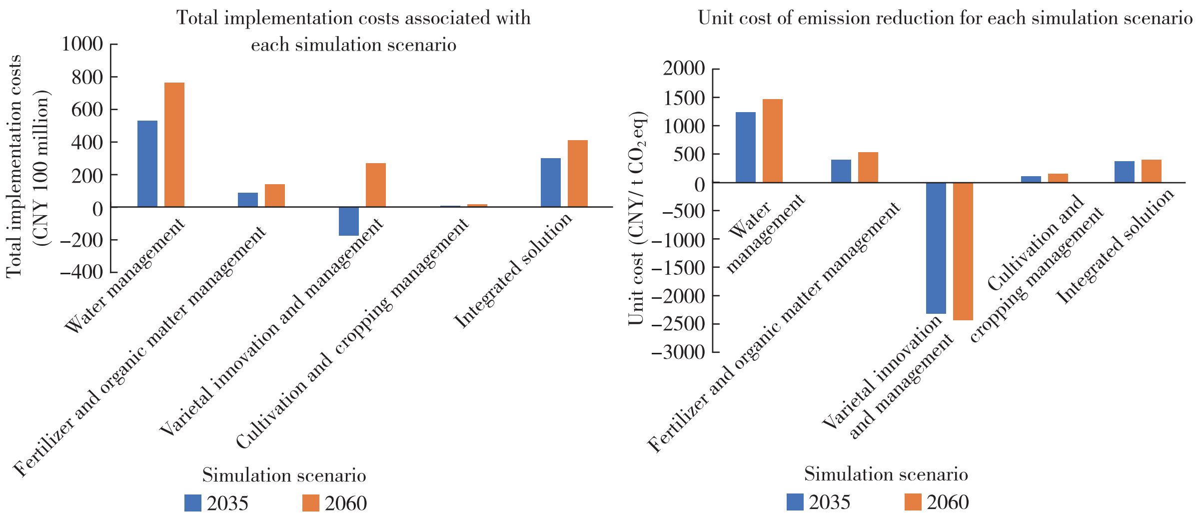
This section presents the projected outcomes of each mitigation scenario in terms of rice yield, methane emissions, total incremental costs, and marginal abatement costs, based on simulations using the China Agricultural University Agrifood System Model (CAU-AFS). For brevity, results under medium-intensity assumptions are reported, as illustrated in Figures 2-4.

Figure 2-4 Yield Increase (%), Methane Reduction (%), Total Implementation Cost, and Marginal Abatement Cost under Various Mitigation Scenarios (Medium-Intensity Assumption).



Data source: China Agricultural University Agrifood System Model (CAU-AFS Model).

Figure 2-4 Yield Increase (%), Methane Reduction (%), Total Implementation Cost, and Marginal Abatement Cost under Various Mitigation Scenarios (Medium-Intensity Assumption).



Data source: China Agricultural University Agrifood System Model (CAU-AFS Model).

Baseline Scenario

Under the business-as-usual trajectory, China's rice production, primarily oriented toward domestic consumption, is expected to decline in response to falling demand. By 2035 and 2060, total rice output is projected to decrease to 192.6 million tonnes and 158 million tonnes, respectively. Cultivated area is estimated to contract to 25.2 million hectares in 2035 and 19.3 million hectares in 2060, marking a substantial decline from 2021 levels. Assuming constant emission intensity per hectare, methane emissions are projected to fall by 15.9% by 2035 and 35.4% by 2060 relative to 2021.

Mitigation Scenario Results

Beyond reducing methane intensity per hectare, most mitigation measures also contribute to yield improvement. Increased yields may reduce market prices, thereby decrease cultivated area and indirectly lowering total emissions. Key findings from each scenario are summarized below:

Productivity Enhancement (SRPROD):

Yield increases by 3% in 2035 and 6.2% in 2060, while methane emissions fall by 6.7% and 12.9%, respectively. This scenario demonstrates strong performance with no additional cost burden.

Water Management (SRWAT):

Yields increase slightly 0.9% in 2035 and 1.5% in 2060. While methane emissions decline markedly by 20.4% and 32.4%. However, implementation entails high incremental costs of CNY 53.1 billion in 2035 and CNY 77.1 billion in 2060, resulting in marginal abatement costs of CNY 1,245 and CNY 1,480 per tonne CO_2eq, respectively.

Fertilizer and Organic Input Management (SRFET):

Output increases by 1.2% and 2% in 2035 and 2060, with corresponding methane reductions of 10.6% and 16.8%. The scenario incurs moderate costs–CNY 8.7 billion and CNY 14.6 billion in the respective years–yielding abatement costs of CNY 393 and CNY 538 per tonne CO_2eq.

Varietal Innovation and Management (SRVAR):

Yield rises by 0.9% in 2035 and 1.8% in 2060, while methane emissions decrease by 3.5% and 6.9%. Notably, this scenario generates positive net economic benefits, adding CNY 17.1 billion and CNY 26.9 billion to farm incomes in 2035 and 2060, respectively.

Cultivation and Cropping Management (SRCUL):

This scenario delivers minor gains in yield–0.2% in 2035 and 0.5% in 2060–and emissions reductions of 4.1% and 8.2%, respectively. However, it results in net costs of CNY 1 billion and CNY 1.9 billion, with abatement costs of CNY 116 and CNY 1,445 per tonne CO_2eq.

Integrated Mitigation Scenario (SRICE):

Combining all five strategies, this scenario produces the most significant improvements: yields rise by 6.2% in 2035 and 11.7% in 2060, while methane emissions decline by 39.1% and 63.8%. Incremental costs reach CNY 30.4 billion and CNY 41.3 billion, translating to abatement costs of CNY 372 and CNY 402 per tonne CO_2eq.

Among the scenarios, the productivity enhancement pathway offers dual benefits with no additional cost, while varietal innovation delivers stable gains with positive net income effects. Fertilizer and organic input management achieves meaningful emission reductions at moderate cost. Water management produces the largest mitigation impact but entails substantial expenditure. The integrated scenario offers the most comprehensive benefits, suggesting that a bundled approach may maximize synergy between emission reduction and productivity enhancement, provided sufficient financial support mechanisms are in place.

Uncertainty Analysis and Comparative Evaluation of Mitigation Scenarios

Given the inherent uncertainties surrounding both yield improvements and methane mitigation outcomes across individual interventions, this study models each scenario under low- and high-effect assumptions. Relative to the baseline, the projected ranges of methane emission reductions by 2060 are as follows: productivity enhancement (6.6%-19%), water management (16.3%-48.4%), fertilizer and organic input management (8.5%-25%), varietal innovation and management (3.5%-10.2%), and tillage and agronomic practices (4.1%-12.3%). The integrated mitigation scenario exhibits the broadest uncertainty band, with potential reductions ranging from 32% to 92.7%, reflecting both its compounded mitigation potential and sensitivity to implementation effectiveness.

2.5 Key Findings and Policy Recommendations

2.5.1 Key Findings

Anchored within the context of China's dual-carbon goals, carbon peaking and carbon neutrality, this study provides a comprehensive assessment of methane emissions from rice cultivation, focusing on current status, historical trends, and forward-looking mitigation strategies. Through detailed emissions profiling, scenario-based projections, and cost-benefit evaluations of key technologies, the study yields the following major insights:

First, while China's total methane emissions from rice cultivation remain high, its emission intensity per unit of rice production is among the lowest globally. Specifically, the emission intensity stood at just 0.7 kg CO_2eq per kilogram of rice. In 2021, total paddy methane emissions reached approximately 248 million tonnes of CO_2eq, representing 26.6% of the country's agricultural greenhouse gas emissions. Globally, China accounted for 21.4% of rice-related methane emissions in 2022.

Second, demographic shifts and declining per capita grain consumption are expected to lead to a gradual contraction in rice cultivation area, particularly in resource-constrained regions or those undergoing structural adjustment. Model simulations suggest that even in the absence of additional mitigation efforts, methane emissions from rice paddies will fall by 15.9% by 2035 and 35.4% by 2060 relative to 2021 levels, driven by reductions in cultivated area. This trend of "structural passive mitigation" provides a critical buffer to support China's agricultural decarbonization agenda and offers a window for scaling up technological innovation and policy integration.

Third, major mitigation strategies vary widely in their effectiveness and economic performance. Water management techniques achieve the highest mitigation outcomes but offer limited yield gains and impose high marginal abatement costs. Fertilizer and organic input management delivers moderate emission reductions and, in some cases, modest yield improvements, though cost-effectiveness remains mixed. Varietal innovation and management emerge as the most economically viable approach, combining strong co-benefits for yields and emissions with relatively low implementation costs. Tillage and cultivation measures show additional mitigation potential, yet their success is highly context-dependent, necessitating site-specific adoption strategies.

Overall, rice methane mitigation represents a high-potential domain with a diverse suite of technical options, offering strategic leverage in driving China's green agricultural transition. However, substantial implementation challenges remain. Mitigation performance and yield stability vary across technologies, while economic viability continues to constrain adoption, especially for approaches requiring high upfront investment, such as precision irrigation and organic matter treatment. Some measures remain at the demonstration stage and are sensitive to local environmental conditions, farmer behavior, and extension system capacity. These findings underscore the need for tailored policy support to de-risk adoption, enhance cost-efficiency, and accelerate scaling of promising solutions.

2.5.2 Policy Recommendations

Drawing on the comprehensive assessment of methane emissions from China's rice sector, the effectiveness and cost-efficiency of available mitigation technologies, and prevailing implementation challenges, this study identifies four key constraints: high technical complexity, weak economic incentives, limited varietal synergies, and low adoption rates. To address these bottlenecks, three strategic policy priorities are proposed: integration of intelligent technologies, upgrading of green seed system, and transformation of agricultural business models.

1. Accelerate the Integration of Artificial Intelligence (AI) to Enhance Mitigation Efficiency

Current water-saving and emission-reducing practices face persistent challenges, including high technical entry thresholds, labor-intensive operations, and low management precision. To overcome these constraints, China should advance the deployment of AI-enabled technologies, such as smart sensors, real-time data acquisition, and machine learning—across paddy field management systems. A coordinated "AI + Agriculture" platform should be established to enable precision control over irrigation, fertilization, and pest management. By reducing labor demand and improving operational efficiency, this approach can enhance the scalability and effectiveness of methane mitigation efforts in rice production.

2. Prioritize Investment in Breeding Low-Emission, High-Nutrition Rice Varieties

Traditional rice breeding programs have long prioritized yield gains, often at the expense of nutritional quality and environmental sustainability. A paradigm shift is urgently needed to promote multi-trait breeding strategies that target yield stability, emission reduction, and nutritional enhancement simultaneously. Substantial increases in public investment and technical support for green breeding initiatives are warranted. Public research institutions should be incentivized to pursue gene pyramiding approaches that target key traits, such as root metabolic regulation, enhanced aerenchyma formation, and nitrogen use efficiency, laying a robust genetic foundation for a climate-smart rice sector.

3. Strengthen the Adoption and Scaling of Methane Mitigation Technologies through policies and institutions changes

Fragmented, smallholder-based production systems remain a major barrier to the diffusion of climate-smart technologies. Policy support should focus on facilitating land consolidation, promoting the transition toward scaled and organized production entities, such as family farms, farmer cooperatives, and modern agribusinesses—and strengthening institutional extension mechanisms for climate-smart agriculture. Complementary financial instruments, including targeted subsidies, green credit lines, and performance-based carbon incentives, should be leveraged to promote widespread adoption of precision irrigation, smart fertilization, and real-time monitoring technologies. These integrated efforts will support the development of scalable, cost-effective methane mitigation pathways across China's rice sector.

References

Chen R, Lin X, Wang Y, et al. 2011. Mitigating methane emissions from irrigated paddy fields by application of aerobically composted livestock manures in eastern China. Soil use and management, 27(1), 103-109.

Chen Z, Han S, Dong Z, et al. 2021. Trade-off between soil carbon sequestration and net ecosystem economic benefits for paddy fields under long-term application of biochar. GCB Bioenergy, 16(1), e13116.

Crippa, M., Solazzo, E., Guizzardi, D., et al. 2021. Food systems are responsible for a third of global anthropogenic GHG emissions. Nature Food, 2, 198-209.

FAO STAT. 2025. https://www.fao.org/faostat/en/#data/GT

Gao R, Zhuo L, Duan Y, et al. 2024. Effects of alternate wetting and drying irrigation on yield, water-saving, and emission reduction in rice fields: A global meta-analysis. Agricultural and Forest Meteorology, 353, 110075.

Gao Y, Cui J, Zhang X, et al. 2025. Cost-effective adaptations increase rice production while reducing pollution under climate change. Nature Food, 1-13.

Hang X, Zhang X, Song C, et al. 2014. Differences in rice yield and CH_4 and N_2O emissions among mechanical planting methods with straw incorporation in Jianghuai area, China. Soil and Tillage Research, 144, 205-210.

Hou H, Yang S, Wang F, et al. 2016. Controlled irrigation mitigates the annual integrative global warming potential of methane and nitrous oxide from the rice-winter wheat rotation systems in Southeast China. Ecological Engineering, 86, 239-246.

Huang J, Nie T, Li T, et al. 2022. Effects of straw incorporation years and water-saving irrigation on greenhouse gas emissions from paddy fields in cold region of northeast China. Agriculture, 12(11), 1878.

IEA (2022), Global Methane Tracker 2022, IEA, Paris https://www.iea.org/reports/global-methane-tracker-2022, Licence: CC BY 4.0

Jin Y, Liu T, Hu J, et al. 2025. Reducing methane emissions by developing low-fumarate high-ethanol eco-friendly rice. Molecular Plant, 18(2), 333-349.

Li J, Wan Y, Wang B, et al. 2024. Annual greenhouse gas emissions from a rice paddy with different water-nitrogen management strategies in Central China. Soil and Tillage Research, 235, 105906.

Li L, Li F, Dong Y. 2020. Greenhouse gas emissions and global warming potential in double-crop** rice fields as influenced by two water-saving irrigation modes in South China. Journal of Soil Science and Plant Nutrition, 20, 2617-2630.

Qian H, Zhu X, Huang S, et al. 2023. Greenhouse gas emissions and mitigation in rice agriculture. Nature Reviews Earth & Environment, 4(10), 716-732.

Shang Q, Cheng C, Wang J, et al. 2021. Net global warming potential, greenhouse gas intensity and carbon footprint as affected by different tillage systems from Chinese double-crop** paddy fields. Soil and Tillage Research, 209, 104947.

Shen N, Tan J, Wang W, et al. 2024. Long-term changes of methane emissions from rice cultivation during 2000-2060 in China: Trends, driving factors, predictions and policy implications. Environment International, 191, 108958.

Vrandečić K, Jug D, Čosić J, et al. 2019. The impact of different conservation soil tillage and nitrogen fertilization on wheat grain infection with Fusarium sp. Poljoprivreda, 25(1), 26-31.

Wang B, Wan Y, Qin X, et al. 2016. Modifying nitrogen fertilizer practices can reduce greenhouse gas emissions from a Chinese double rice crop system. Agriculture, Ecosystems & Environment, 215, 100-109.

Xu X, Zhao Q, Guo J, et al. 2024. Inequality in agricultural greenhouse gas emissions intensity has risen in rural China from 1993 to 2020. Nat Food, 5, 916-928.

Yang J, Gao B, Xia F, et al. 2025. Internalizing the external costs to achieve environmental and economic Goals: A Case study of rice production in China. Food Policy, 132, 102857.

Zhang G, Yang Y, Huang Q, et al. 2020. Reducing yield-scaled global warming potential and water use by rice plastic film mulching in a winter flooded paddy field. European Journal of Agronomy, 114, 126007.

Zhang S, Huang G, Zhang Y, et al. 2023. Sustained productivity and agronomic potential of perennial rice. Nature Sustainability, 6(1), 28-38.

Zhang X, Zhou S, Bi J, et al. 2021. Drought-resistance rice variety with water-saving management reduces greenhouse gas emissions from paddies while maintaining rice yields, Agriculture, Ecosystems & Environment, 2021, 320, 107592.

Chen L, Liu Y, He L, et al. 2024. Carbon sequestration and emission reduction effects of rice straw biochar on paddy soils in southern China. Soil Bulletin, 55(3): 686-694.

Dong Y, Huang J, Li F, et al. 2017. Emissions of methane (CH_4) and nitrous oxide (N_2O) from paddy fields under different irrigation regimes and nitrogen application. Journal of Plant Nutrition and Fertilizer, 23(3): 578-588.

Du Y, Jiang S, Chen Z, et al. 2022. Effects of transplanting date and supplementary irrigation on yield, quality, and resource-use efficiency of the water-saving/drought-tolerant rice cultivar 'Hanyou 73'. Journal of Huazhong Agricultural University, 41(1): 123-132.

Fu Z, Zhu H, Chen C, et al. 2012. Characteristics of CH_4 and N_2O emissions in double-rice cropping systems and variety screening. Environmental Science, 33(7): 2475-2481.

Jiang Y, Qin P, Li Z, et al. 2024. Long-term straw return effects on methane emissions during the rice-growing season in paddy-shrimp co-culture systems. China Journal of Eco-Agriculture, 32(9): 1451-1461.

Li L, Zhou Z, Pan X, et al. 2015. Effects of nitrogen fertilizer and biochar on methane and nitrous oxide emissions in a rice-wheat rotation system. Journal of Plant Nutrition and Fertilizer, 21(5): 1095-1103.

Li X, Wang W, Yang T, et al. 2022. Status, advantages, and key challenges in the development of water-saving, drought-resistant rice varieties. Journal of Huazhong Agricultural University, 41(1): 84-91.

Liao P, Weng W, Gao H, et al. 2024. Current status and development recommendations for direct-seeded rice cultivation technology in China. Scientia Agricultura Sinica (Chinese Journal of Agricultural Science), 57(24): 4854-4870.

Ma C, Pei Z, Li F. 2021. Effects of irrigation regime and nitrogen application on methane emissions and soil organic carbon components in double-rice cropping systems. Journal of South China Agricultural University, 42(5): 41-49.

Peng S, Hou H, Xu J, et al. 2012. Responses of combined

CH_4 and N_2O emissions in rice paddies to controlled irrigation. Transactions of the Chinese Society of Agricultural Engineering, 28(13): 121-126.

Qian D, Hu M, Shen W, et al. 2022. Effects of different organic fertilizer types on rice yield and greenhouse gas emissions in the Pearl River Delta. Journal of Nanjing University of Information Science & Technology (Natural Science Edition), 14(4): 399-409.

Qin X, Li Y, Wan Y, et al. 2014. Effects of tillage practices and straw return on CH_4 and N_2O emissions in double-rice paddies. Transactions of the Chinese Society of Agricultural Engineering, 30(11): 216-224.

Rao X, Sun L. 2020. Impacts of biochar on greenhouse gas emissions (CH_4, CO_2, N_2O) from paddy fields in coastal saline-alkali soils. Journal of Applied and Environmental Biology, 26(6): 1343-1349.

Sun H, Zhou S, Chen G, et al. 2020. Influence of rice cultivar on CH_4 and N_2O emissions from paddies. Journal of Agro-Environmental Science, 34(8): 1595-1602.

Tang S, Liu Y, Jian C, et al. 2022. Review of alternate wetting and drying irrigation: effects on yield, water-nitrogen use efficiency, and rice quality. Journal of Huazhong Agricultural University, 41(4): 184-192.

Tang Z, Zhang J, Deng A, et al. 2022. Spatiotemporal characteristics and mitigation pathways of methane emissions from rice paddies in China. China Journal of Eco-Agriculture (Chinese/English bilingual), 30(4): 582-591.

Wang K, Li F, Fang Z, et al. 2017. Methane emissions from rice paddies under different irrigation regimes and nitrogen application rates, and their relationships with soil organic carbon fractions. Journal of Agro-Environmental Science, 36(5): 1012-1020.

Xie Y, Liao X. 2014. Effects of paddy field management practices on methane emissions. Hubei Agricultural Sciences, 53(22): 5337-5341.

Yin H, Ma Y, Yang S, et al. 2016. Effects of controlled-release compound fertilizer on methane emissions and rice yield in paddy fields. Journal of Phosphate & Compound Fertilizers, 31(1): 49-52.

Zan P, Chen Y. 2018. Study on greenhouse gas emissions and nitrogen use efficiency under different water-fertilizer coupling regimes in rice cultivation. Water-Saving Irrigation, (2): 56-60.

Zhang Y, Chen L, Zhang C, et al. 2015. Effects of mechanized rice planting and transplanting on methane and nitrous oxide emissions from paddy fields. Transactions of the Chinese Society of Agricultural Engineering (Agricultural Engineering Journal), 31(14): 232-241.

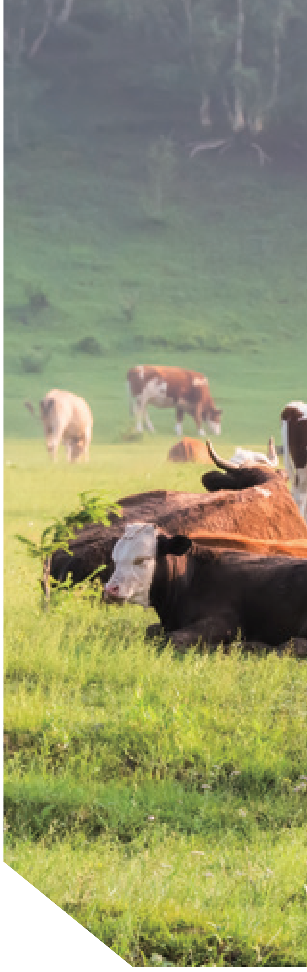
Zhang Z, Han Y, Qi Z, et al. 2020. Effects of straw return and water-nitrogen coupling on CH_4 emissions and yield in paddy fields on black soils. Transactions of the Chinese Society for Agricultural Machinery, 51(7): 254-262.

Zhou H, Wu M, Luo X, et al. 2023. Carbon footprint and economic benefits assessment of different ratoon rice cultivation systems. Journal of Huazhong Agricultural University, 42(2): 71-78.

Sun H, Zhou S, Zhang J, et al. 2020. Synergistic effects of water-saving drought-resistant rice on GHG mitigation and nonpoint source pollution. Shanghai Journal of Agricultural Sciences, 36(5): 79-85.

Chapter 3

Low-carbon Transition of China's Livestock Industry



Ting Meng[1,2], Geping Mao[1,2], Yong Hou[3], Hongliang Wang[3], Lifeng Dong[4], Yumei Zhang[1,2], and Zhaohai Bai[5]

1. Academy of Global Food Economics and Policy, China Agricultural University
2. College of Economics and Management, China Agricultural University
3. College of Resources and Environmental Sciences, China Agricultural University
4. Institute of Feed Research, Chinese Academy of Agricultural Sciences
5. Center for Agricultural Resources Research, Institute of Genetics and Developmental Biology, Chinese Academy of Sciences

Key Findings

● China's livestock industry is a major source of agricultural carbon emissions, with cattle, pigs, and sheep as the the primary contributors. Key emission sources are enteric fermentation and manure management, with cattle, pigs, sheep, and other livestock accounting for 49%, 23%, 13%, and 15% of the total, respectively. Emissions from enteric fermentation are approximately twice those from manure management, while related energy consumption accounts for less than 10%.

● Effective mitigation measures include the use of methane inhibitors, solid-liquid separation and manure acidification, biogas and clean energy adoption, low-carbon breed selection, feed reduction and substitution, and shifting consumption from red meat to white meat. Under a comprehensive scenario simulation, China's livestock industry carbon emissions could decline up to 74% below baseline levels by 2060.

● Several interventions, notably methane enteric inhibitors, improved manure management, and feed grain optimization demonstrate economic feasibility. However, the choice of transformation pathways has complex implications for food security, farmers' income, and resource-environment interactions. Cost-benefits analysis shows that emission reduction measures targeting at enteric fermentation inhibitors, feed, and manure are economically beneficial, while approaches involving seaweed additives, clean energy, and alternative proteins require further cost reduction and efficiency improvement. Thus, transformation pathways should be evaluated holistically, taking into account both economic and environmental impacts.

Policy Recommendations

● Foster Technological Innovation and Optimize Industrial Structure

The livestock industry should promote low-carbon transformation of livestock systems across both production and consumption. The production sector needs to support R&D in breeding superior varieties, apply intelligent breeding technologies for precise feeding, and improve feeding efficiency. On the consumption side, it is crucial to advocate balanced diets, encourage consumption of healthy and low-carbon livestock products, and moderately replace red meat with white meat to reduce emissions.

● Advance Ecological Circulation and Regional Coordination

A sustainable livestock sector can be built through internal ecological recycling and external regional collaboration. The government should encourage crop-livestock circularity and tailor implementation models to different farm sizes and regional conditions. The livestock industry must leverage the demonstration effect of major livestock-producing provinces and regional resource endowments to optimize the spatial distribution of livestock production.

● Establish a Market-based System with Targeted Policy Support

Low-carbon development of livestock industry can be guided through market mechanisms and proactive policy design. Standardized carbon accounting and pilot carbon trading mechanisms, carbon emission monitoring, and certification and regulatory frameworks must be established. The government should develop carbon financial instruments and offer policy incentives, such as tax relief and subsidies, to encourage technological innovation and support livestock enterprises in pursuing low-carbon R&D and application.

3.1 Introduction

The livestock industry embodies the dual characteristics of satisfying essential food demand and representing a major source of carbon emissions. China's livestock sector exerts significant impacts on global climate change and food security, due to its enormous supply and demand scale. Livestock industry provides over one-third of human protein intake, serving as a primary provider of national food livelihood security (Dai et al., 2023). Meanwhile, it represents a major source of greenhouse gas (GHG) emissions within the agricultural sector. Globally, livestock accounts for 14.5% of annual anthropogenic GHG emissions[1], including carbon dioxide (CO_2) from land use and energy consumption, as well as potent non-CO_2 gases such as methane (CH_4) and nitrous oxide (N_2O) emitted directly from livestock systems, which have a high global warming potential (Qin et al., 2024). Correspondingly, the sector also possesses substantial potential for emission reduction[2]. For instance, China's livestock methane emissions could be cut by one-third by 2030 (Wang et al., 2024).

Striking a balance between controlling carbon emissions and ensuring stable livestock supply to meet growing food and nutritional needs while reducing environmental burdens from carbon emissions, and achieving climate mitigation targets, has become a critical challenge for sustainable development. Over the past four decades, China's livestock industry has achieved rapid growth, driven by agricultural policy support and surging consumer demand (Wei et al., 2024; Yao et al., 2017a). Today, China is emerging as one of the world's largest producers and consumers of livestock products. In 2023, China accounted for approximately 46%, 5%, 11%, 15%, and 20% of global populations of pigs, cattle, goats, sheep, and chickens, respectively[3]. Its consumption of pork, beef, mutton, poultry, and eggs represented 48%, 15%, 34%, 18%, and 37% of global totals, respectively[4].

As one of the six key priorities for achieving emission reduction and carbon sequestration in agricultural and rural areas[5], exploring the low-carbon development pathways for China's livestock industry is of practical significance for strengthening food security, modernizing agriculture, promoting ecological civilization and addressing climate change.

Recognizing the urgency of green transformation, Chinese government has issued a series of policy documents to promote low-carbon and high-efficiency development in the sector. The State Council General Office released the *Opinions on Promoting the High-Quality Development of Livestock Industry* in 2020 and emphasized the comprehensive improvement of green breeding standards. The *14th Five-Year Plan for the Development of National Livestock Industry and Veterinary Industry* (2021) requires that by 2025, significant progress will be made in the modernization of animal husbandry nationwide. The breeding of dairy cows, pigs, and poultry will take the lead in basically achieving modernization, and the effectiveness of green development will gradually become evident. Following this, the *Special Implementation Plan for Modern Facility Livestock Industry Construction (2023-2030)* (2023) outlines specific construction objectives, tasks, and layouts for large-scale green farms of various livestock species. The *Guidelines of the Ministry of Agriculture and Rural Affairs on Accelerating the Comprehensive Green Transformation of Agricultural Development and Promoting Rural Ecological Revitalization* (2024) further emphasizes key areas such as the return of livestock manure to farmland for utilization, source reduction, and efficiency improvement in the use of feed and veterinary drugs. *The Low-carbon Evaluation Technical Specification for Large-Scale Dairy Cattle Farms (T/LCAA 014-2024),* the first evaluation standard developed for

[1] According to the FAO report *Tackling Climate Change through Livestock* (Gerber et al., 2013), the total emissions from livestock production were assessed, including direct emissions from livestock, feed production, land-use change, fossil fuel use, and emissions during processing, production, and transportation.

[2] According to Xinhuanet, Livestock industry Has Vast Potential to support Low-carbon Goals, 2022-11-01, https://www.xinhuanet.com/food/20221101/c14f5d7d601e45b7908923a7ef7070fb/c.html.

[3] Data source: Food and Agriculture Organization of the United Nations database (FAOSTAT).

[4] Data source: OECD, https://data-explorer.oecd.org/vis?pg=0&bp=true&snb=3&df[ds]=dsDisseminateFinalDMZ&df[id]=DSD_AGR%40DF_OUTLOOK_2024_2033&df[ag]=OECD.TAD.ATM&df[vs]=&lc=en&pd=2022%2C2024&dq=CHN%2BW.A.CPC_223%2BCPC_EX_SH%2BCPC_EX_PT%2BCPC_EX_PK%2BCPC_EX_BV.QC.T.&to[TIME_PERIOD]=false&ly[cl]=TIME_PERIOD&ly[rs]=COMMODITY&ly[rw]=REF_AREA%2CCOMBINED_UNIT_MEASURE&vw=tb

[5] According to the Ministry of Agriculture and Rural Affairs, Implementation Plan for Emission Reduction and Carbon Sequestration in Agriculture and Rural Areas, 2022, http://www.moa.gov.cn/nybgb/2022/202207/202208/P020220830389177065964.pdf.

the low-carbon performance of large-scale dairy farms, provides valuable guidance for carbon assessment in large-scale pastures. Additionally, a series of policies and plans, including the *Implementation Plan for Emission Reduction and Carbon Sequestration in Agriculture and Rural Areas* (2022), *Methane Emission Control Action Plan* (2023), and *Guidelines of the Ministry of Agriculture and Rural Affairs on Accelerating the Comprehensive Green Transformation of Agricultural Development and Promoting Rural Ecological Revitalization* (2025), provide concrete guidance for low-carbon development.

Against the backdrop of climate change, promoting a low-carbon transition in the livestock industry through diversified, policy-led approaches is not only necessary to safeguard national food security, but also a critical strategy for sustainable ecological development.

This chapter explores the current carbon emission landscape of China's livestock sector and systematically identifies practical mitigation pathways. It synthesizes specific emission reduction measures across key stages, including enteric fermentation, manure management, energy utilization, feed optimization, and consumption-side interventions, while analyzing their economic and environmental co-benefits. By exploring actionable and cost-effective transition options aligned with China's agricultural development, the chapter aims to offer theoretical support and policy recommendations that support both domestic and global efforts to build a climate-resilient, low-carbon livestock industry addressing climate change challenges.

3.2 Current Situation of Carbon Emissions from Livestock Industry

3.2.1 Accounting Boundary, Inventory and Method

In accordance with national standards, the accounting framework for GHG emissions in China's livestock industry follows a structured process around "identification of accounting boundaries, emission source recognition, functional unit division, collection of activity data and emission factors, and GHG emission accounting". It includes defining accounting boundaries, identifying emission sources, establishing functional units, collecting activity data and emission factors, and conducting emissions calculations. The primary approach used is the emission factor.

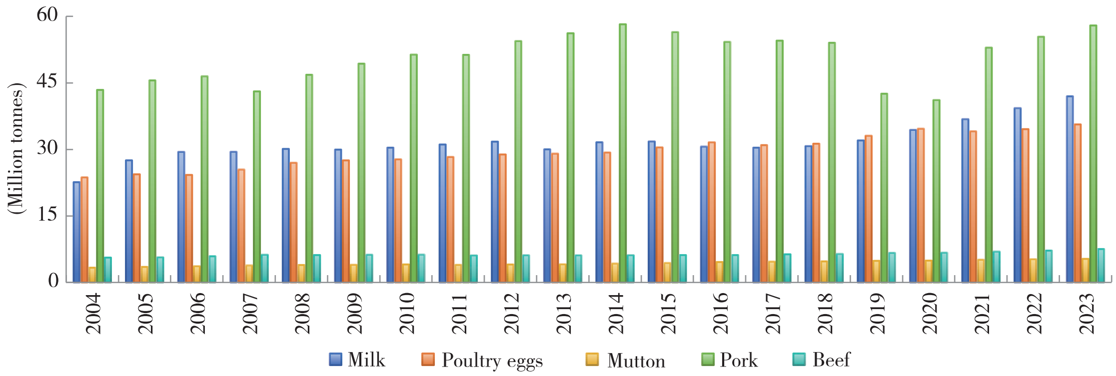
The accounting system boundary is defined by the different production stages within livestock farming that generate GHG emissions, while the temporal boundary is set as one calendar year covering full production cycles. GHG emissions from livestock farming are primarily accounted for across three key dimensions (emission sources): methane emissions from enteric fermentation, methane and nitrous oxide emissions from manure management (covering fecal excretion, cleaning, storage, and treatment), and carbon dioxide emissions from fuel and energy consumption. The livestock species included in the inventory encompass pigs, dairy cattle, beef cattle (non-dairy), sheep, poultry, etc. Energy sources considered include coal, gasoline, diesel, natural gas, electricity, etc.

Mainstream accounting methods in the livestock sector include the IPCC emission factor method and the process-based life cycle assessment (LCA) method. With the successive introduction of carbon accounting standards for China's livestock industry, the accounting methodologies have gradually been unified and improved. The IPCC coefficient method offers advantages of greater comprehensiveness and accuracy, supported by mature accounting formulas and emission factor databases, whereas the LCA method is valued for its systematic and holistic approach to emissions accounting (Xi et al., 2022). Aligning with international standards and China's livestock production practices, a series of local and national standards have been formulated and issued, including *Guidelines for Greenhouse Gas Emission Accounting of Livestock Products (DB 11/T 1565-2018)*, *Guidelines for Carbon Emission Accounting of Livestock and Poultry Farms (DB32/T 4573-2023)*, *Requirements for Greenhouse Gas Emission Accounting and Reporting—Part 22: Livestock and Poultry Farming Enterprises (GB/T 32151.22-2024)*, and *Greenhouse Gases—Methodology and Requirements for Product Carbon Footprint Quantification—Animal Products (GB/T 44903-2024)*. These standards lay a foundation for carbon accounting in China's livestock industry.

3.2.2 Supply and Demand Characteristics of Livestock and Poultry Products in China

On the supply side, the scale of animal husbandry in China has continued to expand in recent years, with steady growth in the production of meat, eggs, and milk (Figure 3-1). The year-end inventory of large livestock such as pigs, cattle, and sheep has remained basically stable. According to the statistical data of China's livestock and poultry products, the output of livestock and poultry products has generally shown an upward trend over the past 20 years. Although pork production has fluctuated (affected by a series of swine fever incidents from 2018 to 2019), it has remained at a high level, and milk production has steadily increased. The output of beef and mutton accounts for a relatively small proportion but has shown an increasing trend.

Figure 3-1 The production of major livestock and poultry products in China from 2004 to 2023

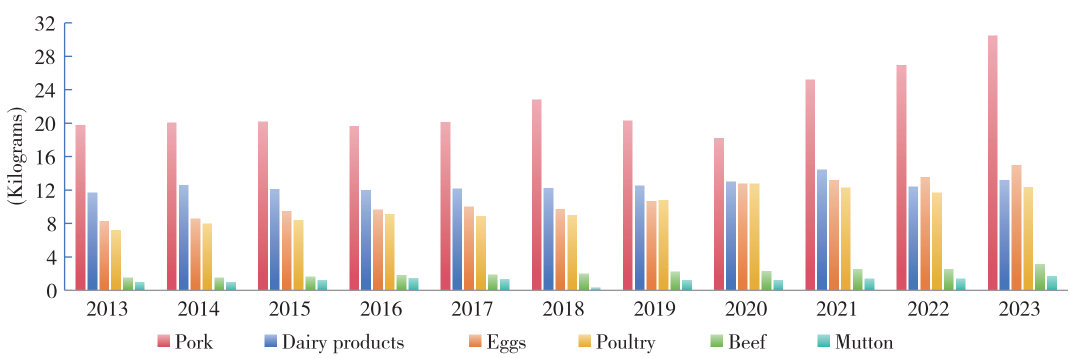


Data source: 2024 China Statistical Yearbook

On the demand side, overall consumption of livestock and poultry products in China has shown a growing trend (Figure 3-2). Consumption of pork, eggs, and poultry meat has continued to rise, dairy product consumption has remained flat, and beef and mutton consumption has increased slightly. Pork remains the primary consumed meat, far exceeding beef and mutton, and has shown an overall upward trend, reaching its peak in 2023, though with some fluctuations.

The growth rates of dairy products, eggs, and poultry are modest, with consumption levels lower than that of pork. Although the consumption of beef and mutton is relatively low, data from the past decade show an overall slow growth trend, which has contributed to a more balanced meat consumption structure. Concurrently, the consumption structure of livestock and poultry products is undergoing a transformation, with increasing consumption of high-protein products such as dairy and eggs, as well as low-fat meats like beef and mutton.

Figure 3-2 Per capita consumption of major livestock and poultry products in China from 2013 to 2023



Data source: China Statistical Yearbook 2014-2024

In recent years, the supply and demand for livestock and poultry products in China have both been robust, yet structural imbalances persist. Based on production and consumption data, the supply and demand for pork and poultry eggs are relatively high, while the output of beef and mutton remains low. Although milk supply has increased, its demand fluctuates. Pork continues to show high levels of both production and consumption, with an upward trend. Meanwhile, beef and mutton represent a smaller share of supply and demand, with only modest growth.

As living standards improve and consumption habits evolve, market demand for high-quality livestock and poultry products continues to rise. The consumption of beef, milk, and mutton gradually increases, thereby driving output growth. From an industrial structure perspective, over the past 40 years, the proportion of meat in the total output has generally declined, the proportion of eggs has remained stable, and milk has shown significant growth. Within the meat category, the proportion of pork production has decreased, while that of poultry meat has increased. Overall, China's livestock industry has not yet fully transition into a high-efficiency input-output optimized stage (Li and Pan, 2022).

3.2.3 Annual Changes and Regional Characteristics of Carbon Emissions from Livestock Industry in China

Livestock-related carbon emissions represent an important source of global GHG emissions, though the sector has exhibited a gradual downward trend in recent decades. From 1995 to 2022, the annual GHG emissions from global livestock industry were approximately 8.5 billion tonnes of carbon dioxide equivalent (CO_2eq). The average annual emissions of carbon dioxide, methane, and nitrous oxide were approximately 1.7 billion tonnes, 4.4 billion tonnes, and 2.2 billion tonnes of carbon dioxide equivalent, respectively (Li et al., 2024). As a major livestock-producing country, China's livestock sector is the primary source of GHG emissions in both agricultural systems and agrifood systems, accounting for approximately 52%[6] of China's total agricultural carbon emissions and 54% of agrifood systems' emissions from agricultural activities[7] (CCICED, 2023). More than 50% of methane and nitrous oxide emissions in the agricultural system originate from livestock (Qin et al., 2024)[8]. In 2021, carbon emissions from enteric fermentation and manure management in China's livestock sector reached 487 million tonnes, with energy use contributing 36 million tonnes of carbon emissions[9].

Total carbon emissions from livestock have fluctuated but generally trended downward, with a steady decline in carbon emission intensity. Moreover, carbon emissions peaked in 2006 (Zhang and Wang, 2020; Tian et al., 2025). In terms of proportion, the share of livestock farming in agricultural carbon emissions has shown an overall stable downward trend (Tian and Yin, 2022).

Regionally, China's livestock industry carbon emissions exhibit remarkable inter-provincial disparities, with a persistent spatial agglomeration pattern. In 2022, Inner Mongolia had the highest provincial-level livestock carbon emissions, while Beijing had the lowest, highlighting a significant regional emission gap. In terms of emission quantity, agricultural areas ranked the highest, followed by agro-pastoral areas, and pastoral areas the lowest. In terms of emission intensity, the distribution pattern generally showed a "high in the northwest, low in the southeast" trend (Shi et al., 2022; Tian et al., 2025).

Spatial analysis further reveals strong spatial dependence and association, meaning that provinces with high emission intensity are adjacent to those with similarly high values, and the same holds for low-emission provinces. In terms of spatial dynamic evolution, livestock carbon emissions have agglomerated toward regions with resource endowment advantages

[6] According to data from *the First Biennial Transparency Report on Climate Change of the People's Republic of China*, and using the IPCC accounting method, China's agricultural activity carbon emissions reached 931 million metric tonnes of CO_2eq in 2021. Among these, enteric fermentation in livestock contributed 322 million metric tonnes of CO_2eq, and manure management accounted for 165 million metric tonnes of CO_2eq.

[7] The carbon emission sources of the agrifood systems are categorized into agricultural activities, factor inputs, food processing, agricultural energy use, and other sources, with livestock carbon emissions falling under the agricultural activities category.

[8] The non-carbon dioxide emission sources in agricultural systems are categorized into three main components: crop farming, animal husbandry, and agricultural waste. Particular attention is paid to methane and nitrous oxide emissions from rice cultivation, agricultural land use, livestock enteric fermentation and manure management, as well as field burning of agricultural waste (Qin et al., 2024).

[9] The carbon emission data of enteric fermentation and manure management are derived from *the First Biennial Transparency Report on Climate Change of the People's Republic of China*. Data on energy use are from Tian et al. (2025).

(grassland pastoral areas and major grain-producing areas). The spatial agglomeration of emission intensity is characterized by a pattern dominated by "low-low agglomeration" supplemented by "high-high agglomeration." "Low-low agglomeration" areas are mainly distributed in southeastern coastal regions, while "high-high agglomeration" areas are primarily located in southwestern, northwestern, and northeastern regions. Together, these two clusters account for more than four-fifths of all provinces.

Meanwhile, the spatial configuration of livestock emission intensity has become increasingly stable, with a pronounced trend of "the high remains high and the low remains low", This growing spatial persistence underscores an intensification of regional development imbalances (Wu et al., 2022; Wang et al., 2025; Tian et al., 2025).

3.2.4 Analysis of Carbon Emissions by Livestock Species

Among all livestock types, cattle, pigs, and sheep consistently rank as the top three emitters in livestock farming, with cattle accounting for the overwhelming majority of emissions. Based on the IPCC coefficient method to account for enteric fermentation and manure management emissions (Figure 3-3), the carbon emissions from cattle, pigs, sheep, and other livestock in 2021 accounted for 49%, 23%, 13%, and 15%[10], respectively. In 2023, using a partial life cycle assessment from livestock rearing to manure treatment, cattle, sheep, pigs, and poultry contributed 74%, 13%, 10%, and 3% of emissions, respectively[11]. Within the broader agrifood systems, ruminants (cattle and sheep) account for 34% of total agricultural activities emissions, followed by pigmeat (9%), milk (7%), eggs (3%), and poultry meat (1%) (AGFEP et al., 2021). The emission shares of cattle, sheep, and poultry have decreased in recent years, whereas the share of pigs has slightly increased (Tian et al., 2025).

Two main factors explain the emission profiles of different livestock species. First, ruminants exhibit significantly higher emission factors for enteric fermentation than other livestock categories, while poultry do not generate enteric methane. Second, China accounts for nearly half of global pig inventory[12], resulting in high emissions due to large size of pig proportion.

There are also significant inter-provincial differences in livestock carbon emission structures, corresponding to variations in local livestock composition. The inter-provincial gap in carbon emission intensity of cattle and sheep has narrowed over time, while the differences in carbon emission intensity[13] of pigs have expanded over time. In 2022, according to the emission structure of livestock species, provincial livestock carbon emissions can be divided into three types: first, cattle breeding-dominated carbon emissions in Qinghai, Ningxia, Guizhou and other provinces, where cattle breeding accounts for more than 60% of carbon emissions. Second, pig breeding-dominated carbon emissions in Guangdong, Jiangsu, Fujian and other provinces, where pig breeding accounts for more than 50% of carbon emissions. Third, multi-livestock breeding-dominated carbon emissions in Jiangxi and Guangxi, where cattle and pig breeding are the main emission sources, while in Henan and Shaanxi, the overall emissions are driven by carbon emissions from pigs, cattle and sheep.

From a dynamic perspective, while the overall carbon emission intensity of pig, cattle and sheep farming has generally decreased in recent years, the trends in inter-provincial differences vary. The regional gap in emission intensity of cattle and sheep breeding has narrowed significantly, while the inter-provincial differences in emission intensity of pig breeding have expanded (Tian et al., 2025).

[10] Based on Figure 3-3, the average proportion of carbon emissions from various livestock species in China in 2020 and 2021 was calculated. The annual average carbon emission proportions of cattle, pigs, sheep, and other livestock were approximately 49%, 22%, 13%, and 15%, respectively (due to rounding for some data, the total may not be exactly 100%).

[11] Based on the study by Ma et al. (2024), the average annual total carbon emissions from pig, cattle, sheep, and chicken farms at a scale of 10000 heads (or feathers) are 996.5, 29462.8, 1644.0, and 17.5 metric tonnes of CO_2eq, respectively. Annual carbon emissions for each livestock category were calculated using year-end inventory data from the *China Rural Statistical Yearbook 2024*.

[12] According to People's Daily, Building a New Pattern for the High-Quality Development of the Pig Industry, 2019-09-12, https://www.gov.cn/zhengce/2019-09/12/content_5429311.htm.

[13] Carbon emission intensity refers to the amount of carbon emissions corresponding to each 10,000 yuan of livestock industry output value.

Table 3-1 Average greenhouse gas emissions per 100 grams of protein products (carbon dioxide equivalent)

Products	Beef (beef herd)	Lamb & Mutton	Beef (dairy herd)	Milk	Pork	Poultry Meat	Eggs
Global: Total emissions (kg)	49.89	19.85	16.87	9.50	7.61	5.70	4.21
China: Production emissions (kg)	13.63	10.87	-	4.03	1.38	0.30	0.44

Note: The first row shows the global average GHG emissions per 100 grams of protein products, calculated using global data. This includes GHG emissions generated throughout the product supply chain, including land-use change, farming, animal feed, processing, transportation, retail, packaging, and waste. Emissions from processing, transportation, retail, and packaging account for a smaller proportion. The second row shows the Chinese average GHG emissions per 100 grams of protein products, calculated using Chinese data. This includes only carbon emissions from the production process.

Data sources: Global data is sourced from Our World in Data, https://ourworldindata.org/grapher/ghg-per-protein-poore; Poore and Nemecek (2018); The Chinese data is calculated based on *the First Biennial Transparency Report on Climate Change of the People's Republic of China* (2024) and annual *National Communications*.

3.2.5 Analysis of Carbon Emissions by Segments

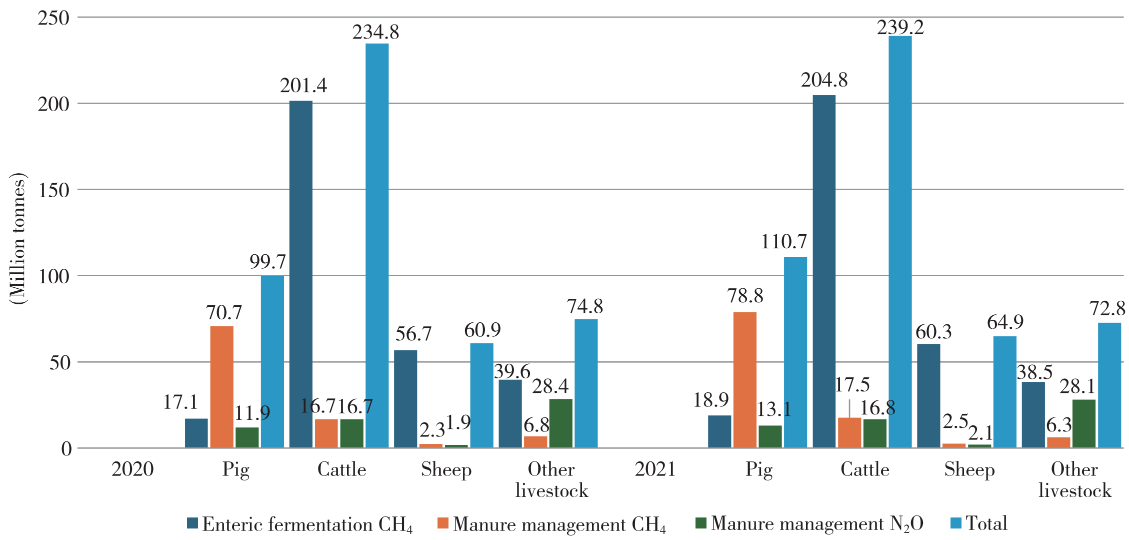
By emission source, enteric fermentation and manure management are the primary contributors to livestock carbon emissions from China's livestock sector, with energy use accounting for a minor share. Considering only enteric fermentation, manure management, and energy use, the average annual emissions from Chinese livestock farming are ranked in descending order: enteric fermentation, manure management, and energy use (Du et al., 2024). In 2021, enteric fermentation emissions were approximately twice those from manure management (Figure 3-3), while energy use contributed less than 10% (Tian et al., 2025). The annual carbon emissions from enteric fermentation in ruminants amount to 180Mt CO_2eq, and those from livestock manure management reach 140Mt CO_2eq (CCICED, 2023).

Emission profiles vary notably across livestock species. For cattle and sheep, methane emitted during feeding constitutes the primary source of emissions, while nitrous oxide from manure treatment represents a secondary component. Pigs' manure contains a high nitrogen content, resulting in the highest nitrous oxide emissions during the manure treatment phase, followed by methane emissions generated in the manure cleaning phase[14]. Poultry (such as chickens) exhibit similar patterns to pigs, with the highest nitrous oxide emissions occurring in the manure treatment stage. Due to their simple digestive systems, however, the proportions of methane and nitrous oxide emitted during the feeding phase are extremely low (Ma et al, 2024).

From a temporal dimension, emissions of methane from manure management and enteric fermentation, as well as nitrous oxide from manure management, have generally declined in recent years, while carbon dioxide emissions from energy consumption in livestock farming have steadily increased. Between 2004 and 2020, carbon emissions from enteric fermentation and manure management generally trended downward, with average annual decline rates of 1.78% and 0.99%, respectively. In contrast, carbon emissions from farming energy consumption showed an overall upward trend, with an average annual growth rate of 7.86% (Du *et al.*, 2024). In terms of GHG composition, methane from livestock enteric fermentation has consistently been the primary emission source, though its overall emissions have decreased—falling by approximately 24% in 2020 compared to 2000. The second-largest contributor is nitrous oxide emissions from manure management, which decreased by approximately 17%, followed by methane emissions from manure management (-11%). With the increasing proportion of non-ruminant animals, particularly the expansion of poultry farming, the share of methane in GHG emissions has gradually declined. Carbon dioxide emissions from energy consumption account for the smallest proportion and have shown the least variation over time (He et al., 2023).

[14] Carbon emissions during livestock and poultry manure cleaning primarily arise from different manure removal methods. Livestock and poultry manure treatment mainly refers to resource utilization, with carbon emissions primarily originating from biogenic emissions generated by organic matter degradation during the treatment process and abiogenic carbon emissions caused by energy consumption inputs (Ma et al., 2024).

Figure 3-3 Carbon emissions from enteric fermentation and manure management of various livestock and poultry in China in 2020-2021 (carbon dioxide equivalent)



Notes: Drawn according to *the First Biennial Transparency Report on Climate Change of the People's Republic of China* (2024). Cattle include beef cattle, dairy cattle, yaks, buffalo, and other cattle. Other livestock in manure management include camels, goats, horses, donkeys, mules, poultry, and rabbits. Other livestock in enteric fermentation include goats, camels, horses, donkeys, and mules.

3.3 Factors Influencing Carbon Emissions from Livestock Industry and Emission Reduction Pathways

3.3.1 Decomposition of Factors Affecting Carbon Emissions from Livestock Industry

Numerous studies mathematically decompose the influencing factors of carbon emissions in livestock industry using analytical methods such as the KAYA identity model, IPAT analysis, LMDI analysis, dynamic data panel model (GMM), and geographically and temporally weighted regression (GTWR). These factors can be primarily categorized into five dimensions: production efficiency, industrial structure, population and labor force, economic factors, and external constraints.

First, production efficiency has consistently been the primary driver inhibiting carbon emissions in livestock industry. Efficiency factors, particularly technical efficiency, have significantly promoted the low-carbon development of GHG emissions in China's livestock industry and represent the most effective pathway for reducing carbon emissions in this sector. At the provincial level, due to differences in the development of livestock industry and technological adoption across provinces, the emission reduction effects of efficiency factors are not stable. Southern provinces generally exhibit a stronger emission reduction effect from efficiency improvements than other regions (Yao et al., 2017b; Bai et al., 2021; He et al., 2023).

Second, structure changes within the livestock industry have had a relatively limited and fluctuating impact on carbon emissions over time. In recent years, the proportion of livestock industry in agricultural structural adjustments has continuously increased, and farmers still rely heavily on income from livestock industry. In 2021, the structure of livestock industry had a positive impact on carbon emissions, particularly in some provinces in eastern and southern China. However, at the provincial level, the contribution of structural factors was less than 10% in most provinces (Bai et al., 2021; He et al., 2023; Zhang et al., 2024).

Third, labor mobility and total population growth have generally driven higher carbon emissions in livestock industry, while urbanization has an inhibitory effect. The promoting effect of population and labor force on carbon emissions can be explained in two ways: first, labor mobility implies a decrease in the demand for labor in livestock industry, which in turn promotes the use of agricultural machinery and increases carbon emissions; second, the growth in total population means a steady increase in the overall demand for livestock and poultry products, which increases carbon emissions but has a relatively small promoting effect (Yao et al., 2017b;

Zhang et al., 2024; Wei et al., 2024). The negative impact of population and labor force on carbon emissions can be explained by the improvement of urbanization, which reduces carbon emissions by promoting the intensification and scale of animal husbandry through the reduction of rural agricultural labor and increasing non-agricultural income to reduce reliance on animal husbandry income (Yao et al., 2017b). Additionally, in the Yellow River Basin, the impact of labor mobility on GHG emissions in livestock industry is on the rise, while the inhibitory effect of urbanization on carbon emissions is gradually declining (Zhang et al., 2024).

Forth, economic development and rising income levels are both important factors promoting carbon emissions in livestock industry. At the macro level, economic factors are positively correlated with carbon emissions, accounting for more than 40% of the carbon emission contribution in most provinces, with higher contributions in northern China provinces (He et al., 2023). In the Qinghai-Tibet Plateau region, carbon emissions from livestock industry are decoupled from economic growth in the sector (Bai et al., 2021). At the micro-individual level, first, an increase in agricultural production efficiency per agricultural population or the average net income per farmer indicates the high economic efficiency of livestock industry production, which will increase farmers' enthusiasm for production and boost demand for livestock products as farmers' incomes rise; second, the disposable income of urban residents has a greater impact on carbon emissions in livestock industry than that of rural residents, as they have higher demand for livestock and poultry products (Yao et al., 2017a; Yao et al., 2017b). Over time, the positive impact of economic development on GHG emissions in livestock industry has shown a downward trend (Zhang et al., 2024).

Fifth, climatic conditions and policy interventions currently exert relatively weak influence on livestock carbon emissions. Taking Qinghai as an example, the impact of climatic conditions such as annual precipitation and average annual temperature on carbon emissions in livestock industry is gradually decreasing, and the main influencing factors of carbon emission intensity are shifting from comprehensive factors such as nature, machinery, economy, and product structure to economic development indicators such as livestock industry output value and urbanization (Li et al., 2025). In addition, due to the low pertinence of policies, external regulations such as the policy environment have a weak inhibitory effect on carbon emissions in the dairy industry (Gan, 2019).

3.3.2 Pathways and Measures for Reducing Emissions from Livestock Industry

Reducing emissions in the livestock industry involves a multi-dimensional approach, encompassing direct carbon reduction or indirect carbon control across three key areas: enteric fermentation, manure management, and energy consumption (Table 3-2). Additionally, comprehensive enhancement in breeding productivity and structural adjustments in product supply, such as protein substitution, are critical levers for mitigation.

In enteric fermentation, rational use of exogenous emission reduction additives and feed improvement can directly reduce methane emissions from ruminants. First, emission reduction additives primarily include plant extracts, probiotics, prebiotics, chemical synthetic inhibitors (e.g., 3-nitrooxypropanol [3-NOP]), seaweed, or their extracts. These additives improve rumen fermentation patterns, reduce methanogen activity, and thereby decrease methane emissions. Plant extracts such as oregano, green tea extracts, and plant essential oils, when used as feed additives, can improve the volatile fatty acid profile and regulate microbial interactions in the rumen without affecting dairy cows' production performance, making them optimal substitutes for antibiotics and synthetic chemicals (Kolling et al., 2018; Belanche et al., 2020; Bature et al., 2024). Probiotics like ruminal probiotic bacteria may enhance rumen digestion in beef cattle and promote a reduction in intestinal methane (Pittaluga et al., 2023). The addition of *Bacillus subtilis* has been proven effective in improving dairy cows' production performance, nutrient digestion and utilization, and reducing intestinal methane emissions (Jia et al., 2022). Halogenated compounds such as 3-NOP, nitrates, and those containing macroalgae can inhibit methane production or compete with methane-producing substrates, among which the enzyme inhibitor 3-NOP demonstrates the greatest in-vivo methane mitigation capacity (Hodge et al., 2024). Additionally, many seaweeds (especially red seaweeds), rich in secondary plant compounds, contain bioactive bromoform that significantly reduces enteric methane production (Abbott et al., 2020; Ondarza et al., 2024). Second, feed processing and quality management involve feed processing and modulation, dietary optimization and by-product replacement of concentrate feed. The primary goal of forage processing is to alter forage morphology (e.g., cutting length, crushing) to enhance palatability and improve microbial digestion of feed ingredients in animals (Weiby et al., 2022), thereby reducing methane emissions. Dietary optimization refers to adjusting feed levels and the sources/proportions of concentrate and roughage to influence gastrointestinal methane emissions, representing the most direct and effective measure for regulating methane emissions. Higher proportions of concentrate feeds (e.g., wheat grains, crushed rapeseed, cottonseed meal) reduce methane production by ruminal methanogens (Beauchemin et al., 2009; Jiao et al., 2014; Moate et al., 2018; Congio et al., 2021). Higher-quality roughages (e.g., adding leguminous plants containing tannins) exhibit greater ruminal digestibility and lower CH_4 emissions (Aboagye and Beauchemin, 2019; Gislon et al., 2020). Supplementing non-protein nitrogen or amino acids to protein diets can also influence methane emissions by altering ruminal microbial community structures, demonstrating promising application effects (Li et al., 2024).

In manure management, GHG emissions from livestock facilities and storage can be reduced through solid-liquid separation, manure acidification, and biogas digester utilization, alongside rational methane recovery. The liquid fraction after solid-liquid separation typically contains high mineral nitrogen and exhibits lower methane emission potential, while the solid fraction, rich in organic matter, requires further drying to reduce overall methane emissions (Petersen et al., 2013). Acidifying manure by adding acidic substances (such as sulfuric acid) reduces the pH value of manure, thereby minimizing GHG emissions (particularly methane and ammonia) during storage and treatment, and improving fertilizer quality (Ólafsdóttir et al., 2023). Adding structurally specialized materials like biochar to manure can effectively reduce nutrient loss during manure utilization and decrease greenhouse gas emissions during manure storage (Lei et al., 2019). Biochar also enhances anaerobic digestion, increasing cumulative methane production (Shen et al., 2022). Additionally, large-scale biogas digesters convert organic matter in manure into biogas via anaerobic digestion, producing renewable energy and replacing fossil fuels to achieve emission reductions (Clemens et al., 2006).

In energy consumption, adopting clean and renewable energy sources alongside manure fermentation systems reduces reliance on traditional energy. On one hand, shifting from fossil fuels to clean/renewable energy (e.g., solar, wind, biomass, geothermal) involves replacing partial shed roofing materials with solar photovoltaic systems and panels to substitute electricity use for feed processing, shed environmental control, shading, and heating (Wang et al., 2017; Maia et al., 2020; Elshimy and El-Aasar, 2020; Minoofar et al., 2023). On the other hand, manure fermentation systems convert greenhouse gases from animal waste into biogas, a critical rural energy source and waste treatment method. The produced energy can be used for activities such as heating and hot water supply, reducing dependence on external energy sources and ultimately cutting carbon emissions (Li et al., 2016).

In comprehensive livestock breeding, productivity and efficiency can be enhanced through multi-faceted strategies including breed selection, feed improvement, veterinary care, herd structure optimization, and pasture management to reduce carbon emissions per unit of livestock product. First, high-efficiency animal breed selection involves screening for breeds with superior feed conversion efficiency and lower relative methane emissions. For example, the heritability of enteric methane production in dairy cows is 0.21, assigning economic weights to methane production in breeding objectives (Haas et al., 2021), selecting dairy cows with higher economic breeding indices (Lahart et al., 2021). Second, substituting concentrate feeds with by-products such as processing residues, food waste, and crop straws uses recyclable agricultural by-products as low-opportunity-cost feed, indirectly reducing agricultural land use, irrigation water, and fertilizer demand associated with feed production and thereby lowering GHG emissions (Fang et al., 2023; Govoni et al., 2023). Third, veterinary care plays a critical role as livestock lifespan and health are closely linked to carbon emission intensity. Improved health management including disease prevention enhances livestock performance (Soosten et al., 2020), with high-performance animals exhibiting lower emission intensity and higher feed efficiency. Fourth, herd structure optimization involves micro-level adjustments such as adjusting the herd structure and the scale of livestock and poultry at different growth stages according to target yields, and formulating management plans to reduce GHG emissions (Liang & Cabrera, 2015; Bokma and Hogeveen, 2024). At the macro level, through systematic management of the livestock and poultry structure, producers can respond to product demand in real time, optimizing carbon emissions while improving supply-demand relationships (Sarttra et al., 2023). Fifth, pasture management practices such as large-scale farming, intensive short-term fattening (e.g., seasonal nomadic farms), and pastoral grazing (involving strategic grazing management such as "continuous rotational grazing" for forage structure and nutritional value) optimize resource use efficiency and livestock productivity to reduce emissions (Savian et al., 2018; Congio et al., 2018; Yetişgin et al., 2022). Beyond these individual measures, integrated crop-livestock systems, nutrient recycling strategies, and green circular economy systems offer comprehensive approaches to GHG mitigation.

To improve the industrial structure, adjusting the structure of livestock products and promoting substitution of livestock meat with aquatic products or alternative protein sources can effectively reduce carbon emissions from livestock production. Reducing consumption of ruminant meat and other livestock products with high carbon emissions helps mitigate short-term GHG impacts (Tong et al., 2023). At the production front-end, adjusting meat consumption patterns and promoting green consumption of aquatic products, such as farmed bivalves and seaweed, can leverage food sources with relatively lower environmental and resource costs (Davis et al., 2016; Li et al., 2023). Additionally, transitioning to more land-efficient and lower-emission alternatives, including plant-based proteins, synthetic starches, and proteins, can partially substitute traditional animal-source proteins, such as red meat and processed meats. Technological pathways based on plant-derived, microbial fermentation, or cell-culture methods hold substantial potential to meet future protein demands while reducing GHG emissions from livestock farming (Nijdam et al., 2012; Collett et al., 2021; Auclair et al., 2024).

Table 3-2 Measures for livestock sector emissions reduction

Dimensions	Subsector	Measures
Key emission reduction links	Enteric fermentation	Exogenous emission reduction additives, feed processing and modulation, optimized feed formulation
	Manure management	Solid-liquid separation, manure acidification, additives such as biochar, use of biogas digesters
	Energy consumption	Clean and renewable energy, utilization of manure-based fermentation systems
Comprehensive enhancement of breeding	Variety breeding	Breeding of high-efficiency low-carbon animal varieties
	Feed substitution	Substitution of by-products for concentrate feeds
	Veterinary care	Health management including disease prevention measures
	Optimization of herd structure	Adjusting herd structure and livestock scale, responding to product supply and demand
	Pasture management practices	Intensive large-scale farming, strategic grazing management strategies
Front-end consumption structure optimization	Front-end optimization	Substitutable proteins, substitution with aquatic products

Note: Summarized and compiled based on the above-mentioned literatures.

3.3.3 Low-carbon Practices in China's Livestock Industry

China has implemented several region-specific low-carbon livestock practices that exemplify ecological integration and sustainable development. Three representative models illustrate how circular economy principles are being applied across the country to reduce carbon emissions and enhance environmental and economic benefits.

1. "Livestock-Biogas-Fruit" Ecological Cycle Model (Guangxi)

In Guangxi, the "livestock-biogas-fruit" ecological cycle model integrates organic fertilizers and biogas generated from livestock manure for fruit tree growth and energy consumption in agricultural parks, forming a typical crop-livestock integration cycle. A typical example is the Guide Citrus Industrial Demonstration Zone as a representative case, this model explores collaborative partnerships between livestock farms and crop enterprises. The Guide Citrus Industrial Demonstration Zone, which fosters collaboration between livestock farms and crop enterprises. Through closed pig shed management, automated breeding, and technical treatment of manure to produce organic fertilizers and biogas energy, the organic fertilizers are applied to citrus cultivation, enhancing tree growth, yield, and fruit quality. Biogas is used for daily operations within the park to save energy, effectively reducing carbon emissions comprehensively and improving ecological benefits.

Case 3.1 The "livestock-biogas-fruit" ecological cycle model

Basic Information

The Guide Citrus Industrial Demonstration Zone base of Nanning Guochen Agriculture and Forestry Company Limited is located in Zhonghe Town, Yongning District, covering a core area of 3,992 mu with a total investment of 186 million yuan. Construction began in 2015 by Nanning Guochen Agriculture and Forestry Company Limited. Over the years, the demonstration zone has evolved into a modern characteristic agricultural zone integrating citrus (specifically Wo Gan oranges) as the leading industry, pig farming, and fishery. It has successively received titles such as the "Guangxi Modern Characteristic Agricultural Demonstration Zone (Five-Star Level)" in 2021 and Nanning's first batch of "Rural Revitalization Women's Demonstration Bases" in 2022. The "Yongchen" Wo Gan oranges have obtained national green food certification.

Typical Experiences

In 2019, building on the successful operation of its citrus base, Guochen Company began exploring diversified crop-livestock integration models and decided to develop pig farming to create a circular economy for harmless waste treatment and efficient resource utilization. In 2020, the demonstration zone invested over 20 million yuan to initially establish an ecological pig farm and partnered with Guangxi Yangxiang Company Limited: Guochen provides the site, equipment, and farmers, while Yangxiang supplies technology and sales channels. Pig sheds adopt fully enclosed management: no personnel are allowed to enter or exit during the five-month breeding cycle to ensure hygiene and safety. The entire farming process is automated, allowing one person to care for hundreds of pigs, with technical advisors and workers on-site to ensure standardized operations. The three pig farms in Guide, Zhoulu, and Tanxi, which are currently in operation or nearing completion, cover an area of 20,000 square meters and are expected to produce 30,000 pigs per year. Additionally, the zone has fully promoted smart farming through internet-connected monitoring, enabling managers to remotely monitor operations.

Manure and wastewater from the farms are centrally collected and processed using anaerobic fermentation, microbial fermentation, and other technologies for solid-liquid separation and resource utilization. After sanitary treatment, organic fertilizers and biogas energy are produced. The zone can annually process 40,000 tonnes of livestock manure, with biogas meeting daily production and living energy needs. This achieves waste recycling, reduces chemical fertilizer and pesticide use, increases economic efficiency, and sets a benchmark for green circular industries.

At the citrus base in the park, huge collection tanks are present. The organic fertilizer produced after processing is directly transported via pipelines to the hills where Wo Gan oranges are grown for irrigation. This saves approximately 3 million yuan in fertilizer costs annually, replenishes nutrient-deficient soil in southern mountainous areas, reduces chemical inputs, improves tree growth, increases citrus yields by 20-30%, and enhances fruit quality. This has significant implications for comprehensive prevention and control of agricultural pollution and the production of green food. The zone also improves soil through understory chicken rearing and intercropping sweet potatoes and soybeans. In the next phase, it plans to introduce aquaculture to further reduce chemical inputs via a "pig-biogas-fish-fruit" ecological cycle, enhancing environmental benefits.

Source: https://www.moa.gov.cn/xw/qg/202109/t20210903_6375672.htm; http://www.yongning.gov.cn/zt/rdzt/ynqxyzl/xydt/t6145329.html.

2. "Grass-Livestock Balance" Ecological Pasture Model (Qinghai)

In Qinghai, the "grass-livestock balance" ecological pasture model emphasizes scientific grass-livestock balance management, rational utilization of forage, and breed selection to form a green and scientific ecological breeding model. Gangcha County serves as a leading example. This model strictly controls grass-livestock balance management, adopts grazing rest and other modes to rationally utilize grassland resources, emphasizes forage reserve and utilization in breeding, customizes forage to improve meat quality, and optimizes livestock breed structure and selection to achieve green, efficient, and low-carbon breeding through multiple approaches. Meanwhile, it enhances operational standards through various intensive development models, establishes interest linkages with farmers and herders, and promotes ecological organic animal husbandry.

Case 3-2 The "grass-livestock balance" ecological pasture model

Basic Information

Gangcha County, located in Haibei Tibetan Autonomous Prefecture, Qinghai Province, lies at the core of two national parks–Qinghai Lake and Qilian Mountains–blessed with superior ecological environment. The county has 637,900 hectares of usable grassland, where nearly 2,000 herder households raise over 300,000 head of cattle and sheep. Since 2015, it has taken the lead in carrying out organic product certification management in selected areas, obtaining the *Organic Conversion Certificate* for cattle and sheep breeding in 2017. As of 2025, it has consecutively held the *Organic Product Certificate* for eight years, achieving basic full-domain certification of organic pastures and becoming the largest organic pasture on the northern shore of Qinghai Lake. In 2023, Gangcha County cultivated and recognized 24 ecological pastures of three categories, with a total scale of approximately 23,000 head of livestock, generating over 47.4 million yuan in total operating income and 21 million yuan in net profit.

Typical Experiences

In terms of grassland-livestock balance management, Gangcha County has scientifically demarcated regions and accurately calculated livestock carrying capacity. The third round of grassland ecological protection subsidies and awards covers 10.7 million mu of grassland, including 3.8 million mu of forbidden grazing areas and 5.8 million mu of grass-livestock balance areas. A total of 85.1 million yuan in policy funds for grassland ecological protection subsidies and awards has been distributed to guide herders to participate in maintaining grass-livestock dynamic balance. Upholding the principle of ecological priority, the county has demarcated regions, given play to the joint responsibilities under the forest and grassland chief system, established a management grid of more than 560 ecological supervisors, introduced joint law enforcement plans, strengthened law enforcement inspections on the implementation of grazing prohibition and grass-livestock balance systems, and investigated and dealt with illegal grazing behaviors. Since June 2024, Ningxia Village in Gangcha County has generated "Grass-Livestock Balance Clearance Cards" by accurately accounting for herders' grassland area, transferred pastures, forage reserves, and livestock numbers, and simultaneously launched a "three-color" early warning mechanism to urge herder households to rectify, ensuring grass-livestock balance and effectively reducing carbon emissions caused by overgrazing.

In livestock farming, Gangcha County has reserved 438,800 tonnes of forage, planted 10,860 mu of forage, completed 1,000 mu of "grain-to-forage" tasks, carried out 2,500 mu of demonstration projects in collaboration with scientific research institutes, enabling nearly 70% of rural and pastoral households and 85% of livestock to achieve supplementary feeding. Ningxia Village has signed contracts with forage factories through cooperative guarantees to ensure forage supply for villagers, and established a "revolving fund pool" to alleviate financial pressures. In cooperation with the Animal Husbandry Academy of Qinghai University, it has customized forage for Tibetan sheep, adjusted the content of nutrients such as protein, effectively solving sheep health problems and improving mutton quality. Meanwhile, it has continuously adjusted the herd structure, optimized livestock breeds, focused on high-efficiency breeding techniques for Tibetan sheep, and the fine breed rate of yaks and Tibetan sheep exceeding 80%. It owns one Tibetan sheep breeding base and fine breed breeding farm. Ecological pastures implement measures such as applying organic fertilizers to natural grasslands, storing forage, and adopting grazing rest, rotational grazing, and semi-stall feeding modes to rationally utilize grassland resources, enhance carbon sequestration capacity, and embark on a path of green and scientific breeding.

Gangcha County combines large-scale breeding, livestock reduction, and forage increase, guides farmers and herders to determine livestock numbers based on forage resources and engage in scientific breeding, promotes intensive development through five models—leading by large households, joint household management, trusteeship services, share cooperation, and village organization leadership—to improve the intensive management level of grasslands, and has built multiple large-scale breeding bases and transferred grassland demonstration sites. It has established interest linkage mechanisms with rural and pastoral households through various forms such as order purchases and employment absorption, driving employment and income growth for small households. Guided by promoting the national agricultural green development pilot zone and building a green organic agricultural and livestock product output base, it is accelerating the cultivation of ecological pastures and creating a efficient ecological circular animal husbandry development model.

Source: http://www.haibei.gov.cn/zwgk/hbxx/dqdt/9325261.html; http://www.qhnews.com/index/system/2025/03/19/030368191.shtml; https://www.gangcha.gov.cn/html/2175/324429.html; http://nmj.haibei.gov.cn/xwzx/jcdt/9173841.html.

3. "Three-Element Bidirectional" Farming-Livestock Circular Model (Gansu)

In Gansu's Zhenyuan County, the "Three-Element Bidirectional" Farming-Livestock Circular Model organically integrates farming-livestock collaboration, waste resource utilization, and industrial chain production to form a sustainable agricultural model of circular development among "animal husbandry-crop planting-edible fungi". This model links broiler chicken farming with corn cultivation, as well as crop-livestock integration with edible fungi production, realizing the feed utilization of crop planting waste and livestock manure from breeding, and returning manure to fields. Through the approach of crop-livestock integration and ecological cycle, it creates a collaborative path for low-carbon agricultural production and income increase for rural residents.

Case 3-3 The "three-element bidirectional" farming-livestock circular model

Basic Information

Zhenyuan County, Gansu Province, located in eastern Gansu, is an important part of the Shaanxi-Gansu-Ningxia revolutionary old area. In recent years, with industrial structure adjustment, Zhenyuan has seen rapid development of livelihood industries such as broiler chicken breeding, grass-livestock farming, melons and vegetables, apples, and medicinal herbs. As a traditional agricultural county, it produces 357,000 tonnes of grain annually, with broiler chicken slaughter volume accounting for 75% of the province's total. Following the development philosophy of "safeguarding grain, strengthening poultry, expanding livestock, increasing vegetables, upgrading fruits, optimizing herbs, and cultivating fungi," it actively constructs a "three-element bidirectional" circular agricultural model based on planting, driven by animal husbandry, and linked by edible fungi, exploring a characteristic path for coordinated ecological and economic development.

Typical Experiences

A closed-loop meat chicken industry chain integrating agriculture and animal husbandry has been deeply established. Zhenyuan closely integrates broiler chicken breeding with corn planting to achieve a closed-loop supply of six modules: "planting-forage-breeding-processing-marketing-residue conversion," creating a high-quality circular industrial chain of "resources-products-waste-renewable resources." The Zhenyuan Three-Element Bidirectional Circular Agriculture Industrial Park exemplifies this model, featuring large-scale broiler chicken farming, high-standardization, and leading market share, driving 418,000 mu of corn planting within the park. The large-scale corn planting base mainly adopts smallholder household contracting and large-scale operation by farmer professional cooperatives. After harvesting, 85% of corn is centrally purchased by in-park feed processing enterprises to ensure feed supply for broiler industries. Corn stalks are processed into feed for cattle and sheep, further extending the livestock industry chain.The park houses three organic fertilizer processing plants, annually treating over 450,000 tonnes of livestock manure to produce 150,000 tonnes of organic fertilizer. When returned to fields, chicken manure-based organic fertilizers not only promote microbial reproduction but also supplement soil organic matter, retain water and nutrients, and boost the yield and efficiency of corn and other crops.

The Yuanshan Three-Element Bidirectional Agricultural Industrial Park constructs a closed loop of "crop-livestock farming-edible fungi production-biological extraction-organic fertilizer production-planting," converting straw and manure into mushroom sticks and fermenting waste mushroom bags into organic bacterial fertilizer for field application, forming a green cycle of "straw for fungi-fungi residue for soil-soil improvement." This model not only solves the traditional challenge of crop rotation but also significantly enhances soil fertility and reduces agricultural material costs. Meanwhile, organic fertilizers derived from livestock manure provide high-quality nutrients for local crops like apples and corn, promoting the realization of crop-livestock circulation and ecological economic goals.

Zhenyuan has built livestock manure treatment centers to process surrounding manure into organic fertilizers, which are used for local crop planting and sold as commodities to surrounding areas, forming a green path of nearby waste utilization, resource conversion, crop-livestock integration, and ecological circulation. Adhering to the strategy of industrial prosperity for residents, the county provides 56,200 households with full-process services of "planting-breeding-processing-marketing," efficiently recycling 31 million mushroom sticks and 10,100 tonnes of agricultural waste—fully demonstrating the dual value of circular agriculture in ecological protection and farmer income growth.

Source: https://baijiahao.baidu.com/s?id=1787502422094061150&wfr=spider&for=pc; https://baijiahao.baidu.com/s?id=1830817393806229240&wfr=spider&for=pc; https://baijiahao.baidu.com/s?id=1797648838579478457&wfr=spider&for=pc; https://www.gszy.gov.cn/xwzx/shxw/content_69899; https://baijiahao.baidu.com/s?id=1830721796193445767&wfr=spider&for=pc; https://www.gszy.gov.cn/xwzx/shxw/content_85627; https://baijiahao.baidu.com/s?id=1807783840066301835&wfr=spider&for=pc.

3.4 Emissions Reduction Potential, Cost-benefit analysis, and Impact of Low-carbon Transition Pathways

3.4.1 Analysis of Emissions Reduction Technologies and Potential

Livestock emissions reduction can be achieved through multiple pathways across the production process, namely enteric fermentation, manure management, energy consumption, and comprehensive livestock farming management. This section evaluates the potential and effectiveness of key mitigation technologies and practices, based on recent empirical evidence and data from 2021.

● Enteric Fermentation

In the enteric fermentation process, examine the effects of two intestinal methane inhibitors (3-NOP and seaweed) and dietary optimization. Among methane inhibitors, adding 3-NOP to dairy and beef cattle diets reduces enteric methane production by an average of 30% (Yu et al., 2021), with efficiency positively correlated with 3-NOP dosage. Based on the 2021 livestock emission data (Figure 3-3), using 3-NOP could reduce carbon emissions from Chinese cattle by 61.4 million tonnes, a 25.7% decrease in total cattle emissions and a 12.6% reduction in overall livestock carbon emissions. Supplementation of 0.5% *Asparagopsis taxiformis (AT)* in dairy cow diets decreases enteric methane emissions by 55%-65% (Stefenoni et al., 2021). Calculated by the 11% proportion of dairy cows in the cattle herd, carbon emissions from cattle (in CO_2eq) would decrease by 12.39-14.65 million tonnes, accounting for 5.2%-6.1% of total cattle emissions and 2.5%-3.0% of overall livestock emissions[15]. On average, these results show that intestinal methane inhibitors could reduce overall livestock carbon emissions by 2%-13%, particularly through increased 3-NOP use, which more effectively mitigates direct carbon emissions from cattle gastrointestinal tracts. Dietary optimization, such as adding wheat grains to dairy cow diets reduces methane emissions by 45% (Moate et al., 2018). Based on 2021 data, this would decrease methane-related carbon emissions from dairy cows by 10.14 million tonnes, accounting for 4.2% of cattle GHG emissions.

● Manure Management

In the manure management process, examine the scenarios of acidification treatment, solid-liquid separation, biochar addition, and biogas collection. Acidification of manure reduces emissions of ammonia, methane, and nitrous oxide during storage, however, the impact of acidification on GHG emissions varies depending on pH and temperature (Sokolov et al., 2019; Sokolov et al., 2021; Dalby et al., 2022). Sulfuric

[15] According to the data from *China Rural Statistical Yearbook 2022*, the year-end inventory of dairy cows nationwide was 10.9 million heads in 2021, accounting for approximately 11% of the total year-end inventory of cattle (98.2 million heads).

acid treatment of liquid dairy manure at pH 6 reduces GHG emissions (in CO_2eq) by 88% (Sokolov et al., 2019). Adding 10% biochar to pig manure reduces cumulative carbon dioxide and nitrous oxide emissions by 15.4% and 19.8%, respectively, compared to untreated manure (Lei et al., 2019). Adding 5% biochar to anaerobic digestion of chicken manure as a substrate increases cumulative methane production by 12%-69% (Shen et al., 2022). Manure treatment processes like anaerobic digestion (e.g., biogas digesters) and solid-liquid separation reduce GHG emissions. Heat treatment during storage enhances methane production potential by 16%-35% (Ólafsdóttir et al., 2023). Compared with untreated manure slurry, solid-liquid separation and anaerobic digestion reduce greenhouse gas emissions by 31% and 25%, respectively (Holly et al., 2017). Thus, manure management, especially solid-liquid separation and anaerobic digestion in biogas digesters, holds significant potential for livestock emission reduction.

● Energy Consumption

In the energy consumption process, by leveraging clean energy and manure fermentation systems, it is possible to effectively control the use of non-renewable energy sources and achieve emission reduction targets. Studies show animals prefer shading under photovoltaic panels, and increased solar radiation boosts photovoltaic energy production. For example, placing 11 sheep in a shaded enclosure with 10 photovoltaic panels generated 5.19 MWh of electricity annually, reducing carbon dioxide emissions by 2.77 tonnes (Maia et al., 2020). Converting animal manure into biogas saves approximately 20% of natural gas usage (Li et al., 2016). This would save 75.46 billion m^3 of natural gas equivalent to energy input from animal excrement[16]. In non-renewable energy, electricity is the most wasted input in buffalo farms. If all farmers follow the optimal inputs recommended by artificial neural networks, total energy use could decrease by 30.5% (Elahi et al., 2019).

● Comprehensive Livestock Farming Management

In integrated pasture management measures, examine the scenarios of high-economic-breed selection and pasture grazing strategies. Selecting dairy cows with high economic breeding indices reduces GHG emissions per kilogram of milk solids by 11% (Lahart et al., 2021), and selective breeding could lower enteric methane intensity in dairy cows by 24% by 2050 (Haas et al., 2021). Based on this rough estimate, GHG emissions from dairy cows could be reduced by 11%, equivalent to 2.89 million tonnes. Grazing management also differs in impact, sheep raised under transhumance systems emit 18% less CO_2eq per kg live weight (20.8 kg CO_2eq/kg) than those under semi-intensive systems (25.4 kg CO_2eq/kg) (Yetişgin et al., 2022). Proper grazing management strategies under continuous and rotational grazing reduce methane emissions per unit average daily gain by 22% and 35%, respectively (Congio et al., 2021). Thus, substituting semi-intensive farms with transhumance systems could reduce sheep emissions by 18%, decreasing 2021 livestock carbon emissions (Figure 3-3) by approximately 2.4%.

Besides this, adjusting livestock structure such as substituting low-carbon for high-carbon species or adjusting the structure within livestock species can regulate overall emissions. Replacing beef with low-carbon poultry or pork requires 337.5 poultry to substitute for 1 cow[17], making its contribution to livestock emission reduction debatable due to the large substitution ratio. Varying the proportion of first-lactation cows in dairy herds can reduce GHG emissions by 3.4%-7.3% (Liang and Cabrera, 2015). Based on 2021 data, this could lower dairy cow emissions by 0.89-1.92 million tonnes, accounting for 0.4%-0.8% of total cattle emissions and 0.2%-0.4% of overall livestock emissions.

Overall, enteric methane inhibitors, improved manure management, energy transition, and superior breed selection exhibit substantial potential for emission reductions. Core mitigation measures include using 3-NOP in animal feed, manure acidification, solid-liquid separation, anaerobic digestion via biogas systems, photovoltaic energy substitution, and the adoption of high-economic-index breeds. Integrating these measures is expected to unlock greater emission reduction opportunities across the livestock sector.

[16] According to the data from the *China Energy Statistical Yearbook 2023*, and in line with the estimation benchmark of 2021 for the enteric fermentation, the national natural gas consumption of 377.30 billion cubic meters in 2021 is selected for the estimation.

[17] With reference to the calculation method of Tian and Chen (2021), the *Emission Standard of Pollutants for Livestock and Poultry Breeding Industry* (GB 18596-2001) converts the breeding quantity of different types of livestock according to coefficients. After taking the average value, one dairy cow is equivalent to 450 chickens, one beef cattle is equivalent to 225 chickens, and one cattle is equivalent to 337.5 chickens.

3.4.2 Cost-benefit Analysis of Emission Reduction Technologies

While emission reduction technologies offer substantial potential for GHG mitigation, their large-scale adoption faces practical challenges without sufficient economic feasibility.

Among methane inhibitors, 3-NOP and seaweed demonstrate substantial abatement potential, with 3-NOP being more economically viable. 3-NOP demonstrates superior efficacy in mitigating intestinal CH_4 in livestock, maximizing GHG reduction, but its cost (77$ $head^{-1}$ yr^{-1}) hinders widespread adoption (Han, 2024). Based on the price of carbon, dairy and beef producers should pay no more than $46-51 and $33-45 per kg of 3-NOP respectively to maintain profitability. Low dosage requirements and high methane suppression efficiency partially offset its costs (Alvarez-Hess et al., 2019). Several macroalgae species have been proposed as novel ingredients in ruminant diets, but their production and application face challenges. In addition to the high production costs associated with resource-intensive cultivation, harvesting, processing, and downstream storage, transportation, and processing of protein extraction (seaweed is highly perishable, requiring strict temperature control to prevent spoilage) (Monteny et al., 2006; Wanapat et al., 2024; Sun et al., 2024), there is also a lack of evidence to demonstrate that using seaweed components to reduce methane. Current seaweed cultivation cannot meet demand, necessitating production shifts to non-traditional sea areas. Establishing large-scale industrial facilities requires high costs and labor, leaving sustainable and economically feasible seaweed farming facing technical hurdles. Existing large-scale facilities lack the capacity to produce the massive biomass needed for the global animal feed industry (Kulshreshtha et al., 2020; Sun et al., 2024).

Manure management is one of the most accessible areas for achieving emission reduction targets (Han, 2024). Solid-liquid separation and anaerobic digestion yield net economic benefits across the manure treatment chain. Acidification treatment costs derive from equipment and reagents, amounting to 8.00 yuan per tonne of manure, but the social benefits from ammonia emission reduction (3.57 yuan) exceed the acidification cost. The most cost-effective acid dosages for 1-3 treatments and 10 treatments are 2.1 and 3.2 kg/m^3, respectively (Sokolov et al., 2019; Ma et al., 2022; Wang et al., 2024). During manure storage and treatment, solid-liquid separation and reactor composting equipment incur higher unit costs (38.00 yuan) than traditional technologies, but generate social benefits of 43.07 yuan (Wang et al., 2024). In anaerobic digestion, annual treatment costs in Lanzhou average 23.75 $yuan/m^3$ with corresponding benefits of 27.74 $yuan/m^3$. Of this, one-third of the benefit is generated from biogas power generation (Wang et al., 2023). The wet anaerobic fermentation technology for dairy manure requires an average investment of 2,777 yuan per cow and an operational cost of 467 yuan per cow, with a payback period of approximately four years (Luo et al., 2020). Notably, uncontrolled pH and acidification degree in the acidification process directly affect gas emissions (Cao et al., 2020). Additionally, farm scale influences cost-benefit ratios. Small-scale farms may face higher biogas investment costs than returns, while large-scale farms can cover losses with subsidies (Chen et al., 2017; Li et al., 2022). Biochar, as a low-cost, renewable carbonaceous material, features high specific surface area, strong conductivity, and rich surface functional groups, but its effectiveness and comprehensive benefits in anaerobic digestion engineering remain to be evaluated (Shen et al., 2022).

Adopting integrated clean energy systems, such as photovoltaic and biogas technologies, involves significant upfront investment but proves economically viable primarily for large-scale farms. Among energy management strategies, reducing energy intensity and adjusting energy structure to cut diesel usage are cost-effective (Li et al., 2024). Photovoltaic power generation is increasingly being combined with livestock production as a supplement to fossil fuel savings (Lauer et al., 2018). A 10-panel solar system can save $740 annually in electricity costs (Maia et al., 2020), but only large farms with over 1,000 heads currently have the economic capacity to build and operate photovoltaic facilities (Han, 2024). The estimated comprehensive cost of purchasing and installing distributed photovoltaic modules is 3.22 yuan/W, and the operation and maintenance cost can reach 0.03 yuan/W per year (Pang, 2023). Additionally, the combined application of solar energy and biogas systems, which features solar heating and biogas slurry recycling, offers significant economic value. Compared with conventional equipment, this approach can reduce total investment costs by 8.5% and increase gas production by 12.3%, balancing economy and environmental protection (Li, 2023). However, biogas management commonly suffers from methane leakage, particularly in small-scale digesters in Asian countries, where methane losses can reach 40% (Bruun et al., 2014).

Livestock management involves trade-offs between feed costs, productivity, and product premiums, complicated by challenges in real-time feed efficiency assessment. Increasing grain use in feed must consider not only higher chemical nitrogen fertilizer and fossil fuel consumption from machinery but also the cost comparison between grain and traditional feed (Løvendahl et al., 2018). In contrast, reducing crude protein in animal feed is a cost-effective alternative, with the lowest adoption cost and savings in protein-rich feed consumption (Xu et al., 2022). Additionally, precision feed formulation and fine processing centered on low-protein diets can effectively reduce soybean meal use (Li et al., 2024). Dairy cows relying primarily on pasture with limited concentrate feeding exhibit lower average milk production and daily feed-cost income ($5.76 per cow). However, enhanced feed quality and optimized feeding practices can effectively boost livestock weights and product yields, the premium of organic grass-fed milk can potentially offset partial production losses (Hardie et al., 2014; Congio et al., 2021; Li et al., 2024). Considering yield and cost comprehensively, dairy cows with a high economic breeding index have higher total feed and energy demands but yield more milk, fat, and protein, leading to higher sales and overall profitability (O'Sullivan et al., 2020). However, pasture grazing systems diminish milk, butterfat, and protein yields, and these production losses often outweigh the savings in feed costs (Brito et al., 2022). Current nutritional research also shows that accurately measuring feed intake and related output traits is necessary to express dairy feed efficiency, but emission and efficiency data from low-intake periods poorly correlate with those from other lactation stages, posing challenges for timely feed efficiency assessment (Almeida et al., 2021).

Alternative proteins offer promising substitutes for conventional animal products with significant environmental and market potential. Replacing livestock products with alternatives could liberate agricultural land for dual climate benefits (Collett et al., 2021). However, energy consumption costs must be considered. For instance, bacterial protein production requires non-toxic and sterile environments (Lee, 2014), with production costs dominated by electricity consumption in electrolysis. Bacterial protein costs are 50-80% lower than animal-derived products, but the process is highly energy-intensive, dependent on power supply, and constrained by economies of scale and electricity prices (Collett et al., 2021). Compared to the high R&D investment in bacterial proteins, plant-based meat analogs have lower production costs and natural ingredients (Liu et al., 2021), making them a more economical alternative protein choice.

In conclusion, economically viable pathways for reducing livestock emissions currently include exogenous additives represented by 3-NOP, manure management, and feed optimization. Emerging solutions such as seaweed additives, alternative proteins, and renewable energy integration require further R&D to improve cost competitiveness. Achieving sustainable low-carbon development in the livestock sector will depend on aligning technological feasibility and economic viability.

Table 3-3 Emission reduction potential and costs

Links	Measures	Emission reduction potential	Cost analysis
Enteric	3-NOP	Adding 3-NOP to the feed of dairy cows and beef cattle can reduce intestinal CH_4 production by an average of 30%.	High cost of 3-NOP($77 per head per year)
	Seaweed	Adding 0.5% *AT* to the daily diet of dairy cows can reduce intestinal CH_4 emissions by 55%-65%.	1) High production costs including cultivation, harvesting, processing, protein extraction; 2) Control the storage environment to prevent seaweed from molding and deteriorating.

Links	Measures	Emission reduction potential	Cost analysis
Enteric	Optimized feed grains	Adding wheat grains to the diet of dairy cows can reduce CH_4 emissions by 45%.	1) Costs of nitrogen fertilizers for grain input, machinery fuel, and feed allocation; 2) Difficult to timely assess feed efficiency; 3) Product premiums and increased product output from feed optimization offset some production losses; 4) Reducing crude protein in feed incurs the lowest adoption cost and can save feed consumption.
Manure	Manure acidification	Acidification reduces the total GHG emissions from liquid manure slurry by 85%-88%.	1) Costs of purchasing acidifying equipment and reagents, and adjust the frequency of acidification for cost-control; 2) Difficult to control pH value and degree of acidification during the process.
	Solid-liquid separation	Solid-liquid separation can reduce GHG emissions by 31%.	Costs of equipment and reactor composting equipment, with a unit treatment cost of 38.00 yuan.
	Anaerobic digestion	Anaerobic digestion can reduce GHG emissions by 25%.	Engineering operation costs, with an investment payback period of approximately 4 years.
	Biochar	Adding biochar during manure storage can reduce carbon emissions, while its addition in anaerobic digestion can enhance cumulative methane production.	Low-cost and renewable, but the actual application effect and comprehensive benefits remain to be evaluated.
Energy	Alternative energy	The energy generated by photovoltaic panels provides electric power	High business threshold, only large-scale pastures have the capacity for construction and operation.
	Biogas	Biogas produced from animal excreta converted into energy can save 20% of natural gas consumption.	Difficult to manage, with widespread CH_4 leakage.
Breeding	Pasture management practices	Sheep raised under transhumance systems emit 18% less carbon per kg live weight than those under semi-intensive systems	
	Variety breeding	Selecting dairy cow breeds with high economic breeding indices can reduce GHG emissions per kilogram of milk solids by 11%.	Higher total production revenue and overall profitability.
Front-end	Alternative proteins	Optimize land resource utilization and reduce carbon emissions	High R&D investment and high electric energy consumption.

Note: Summarized and compiled based on the above-mentioned literatures.

3.4.3 Impacts of Emission Reduction Pathways on Food Security, Farmer Incomes, and Resource Environment

The implementation of emission reduction measures in livestock systems is closely linked to food quantity and quality security, farmers' incomes, and environmental sustainability. These measures generate both positive impacts on food production and the economy, as well as negative consequences, particularly related to pollution risks in soil, atmosphere, and water bodies. Broadly, the adoption of emission reduction pathways promotes the overall transformation and upgrading of the livestock industry, though the associated impacts vary across different economies and production systems.

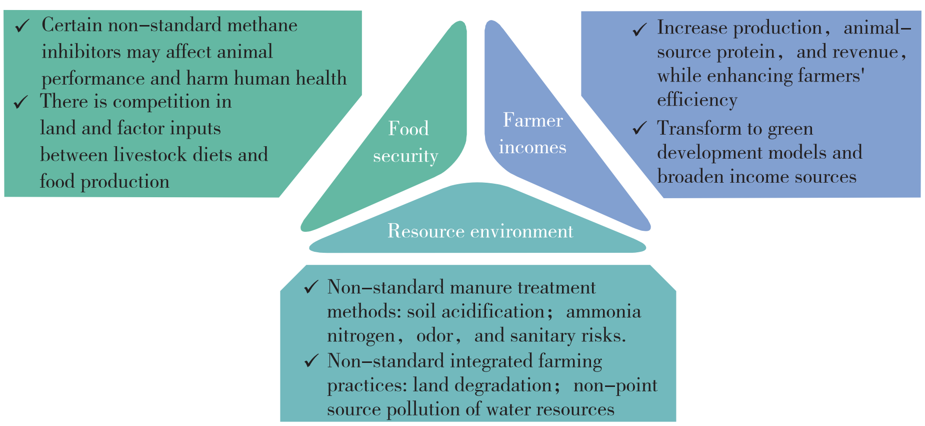
The use of certain methane inhibitors and feed-based interventions may influence food security outcomes. First, improper use of methane inhibitors in animal feed may directly impact product quantity and quality safety. The methane-reducing effect of seaweed in animals is primarily attributed to the compound bromoform, especially in red seaweeds. As feed, it may impact animal production performance, and the high-level bioactive secondary metabolites in seaweed could negatively affect rumen digestion and animal health. The related impacts on livestock and humans after seaweed consumption remain to be evaluated (Abbott et al., 2020; Wanapat et al., 2024). Meanwhile, bromoform may be associated with carcinogenicity and renal/hepatic toxicity. Macroalgae also contain heavy metal ions (e.g., lead, arsenic, cadmium, mercury) and plastic particles, as well as high iodine content. Excessive intake may harm ruminants and human health through the food chain (Huang et al., 2022; Wanapat et al., 2024; Sun et al., 2024). Second, competition and trade-offs in factor inputs between food and feed production indirectly affect the quantity security of livestock products. Providing food through animals incurs substantial conversion losses, creating a significant trade-off between producing food for direct human consumption and animal feed. Most grasslands are unsuitable for cropland production, and balancing ruminant production based on grasslands with the quantity of main feed ingredients from farmland in livestock diets imposes endowment pressures on both livestock and food production (Schader et al., 2015).

Poorly managed manure handling practices and integrated farming systems can lead to significant environmental risks to soil, atmosphere, and water environments. Although acidified manure can retain nitrogen in soil, reduce NH_3 volatilization losses, and improve soil fertility, unstandardized acidification storage technologies and application methods can diminish manure fertility, even causing secondary pollution and soil acidification (Zhang et al., 2023). Different solid-liquid separation technologies exhibit significant variations in nutrient loss and associated environmental risks. Solid-liquid separation technologies also fail to effectively remove ammonia nitrogen, odors, and sanitary risks (Jiang et al., 2016). Pollution from manure storage, technology application management chains, and pretreatment processes requires further evaluation to mitigate impacts on biogeochemical cycles, soil microorganisms, and edaphic quality (Zhang et al., 2022). Additionally, land degradation driven by soil erosion and nutrient depletion is pervasive in pastoral ecosystems. Non-compliant intensive farming practices and grazing management regimes may result in imbalanced or excessive nitrogen and phosphorus inputs in livestock production systems, thereby exacerbating non-point source contamination of water resources and threatening biodiversity (Sakadevan et al., 2017).

Some low-carbon practices enhance farmers' incomes by improving production efficiency and creating employment opportunities. When balancing economic synergies that integrate productivity, profitability, and opportunity costs, actions like adjusting livestock structures, enhancing animal health, and optimizing feed inputs can elevate animal-source protein production (Congio et al., 2021) and yield levels to increase returns, especially in low- and middle-income countries (Bateki et al., 2023). Meanwhile, solid-liquid separation and anaerobic digestion in manure management expand income sources through renewable energy operations, exerting positive impacts on economic benefits. However, the effects of renewable and alternative energy on economic benefits are positive or neutral, the economic impact of adding 3-NOP methane inhibitors to feed remains unclear, and the economic effect of adding seaweed is directionally uncertain (Harrison et al., 2021). Additionally, the transition to green development such as enhancing manure resource utilization and integrating planting with breeding ultimately enhances agricultural production efficiency (Ma and Xiao, 2024), broadens employment avenues for rural surplus labor, drives farmer income growth, and fosters income generation across multiple sectors (Shao, 2024).

Low-carbon livestock transformation inevitably entails industrial restructuring, and upgrading, with differing implications for farms of varying sizes and economic contexts. First, the substitution and upgrading of old and new technologies. Within farms, measures such as solid-liquid separation in manure treatment, acidification facilities, biogas digester construction, optimized barn manure cleaning and clean energy substitution require advanced equipment and technologies to achieve emission reduction goals. This imposes costs for technology updates and equipment maintenance on farms, especially small and medium-sized enterprises, placing them at a disadvantage in market competition. Second, changes in market competition patterns. In the upstream and downstream links of livestock production, related industries such as R&D, feed processing, equipment manufacturing, transportation, and consumption are also affected. Enterprises that take the lead in achieving low-carbon development will gain a competitive edge as global demand for animal products grows, further intensifying market competition fluctuations. Additionally, as developing economies account for the largest share of livestock product demand growth (Makkar, 2018), high-skill emission reduction approaches like early-life management planning and genetic selection require high-skill inputs, cannot effectively reduce methane emissions in ruminants. Management and nutritional strategies related to emission reduction will yield the greatest and most direct impacts at the lowest cost (Goopy, 2019). Consequently, industry disruptions may differ significantly between high-income and low/middle-income economies, as well as between large-scale and smallholder enterprises.

Figure 3-4 The impacts of emission reduction pathways in livestock industry on food security, farmers' income and resource environment



3.4.4 Simulation of Emissions Reduction Pathways for the Livestock Industry

To assess the future carbon emission reduction potential of China's livestock industry, this study employs the CAU-AFS Model (CAU-Agrifood Systems Model) of China Agricultural University to simulate the supply and demand of agricultural products and the related carbon emissions in China from 2026 to 2060. The results under business-as-usual assumptions serve as the baseline scenario. Building on the analysis of the emission reduction pathways, and considering the projected proportion of large-scale operations, the study assumes promotion rates for different mitigation technologies and simulates six alternative scenarios, namely, improving animal productivity, optimizing animal feed, regulating rumen, managing animal manure, adjusting dietary structure, and a comprehensive emission reduction strategy in livestock industry, are designed to simulate the GHG emission reduction. Details are shown in Table 3-4.

Animal Breeding Simulation Scenario (LPROD): This scenario assumes that technologies such as genetic selection will accelerate livestock traits, leading to high yields, better feed conversion ratios, and lower methane emissions. This scenario assumes that by 2035, the animal productivity can be increased by 10%, and by 2060, the productivity can be increased by 30%. With the feed consumption remaining unchanged, the carbon emission intensity will decrease by 10% and

30% accordingly.

Feed Optimization Simulation Scenario (LFEED): This scenario incorporates measures such as precise feeding and low-protein diet formulations. It is assumed that the feed conversion rate will increase by 10% in 2035 and by 20% in 2060. The low-protein diet technology can reduce the nitrogen content in animal excreta by reducing the use of protein feed in the animal diet and supplementing the required amino acids at the same time, and the nitrous oxide emissions from livestock and poultry manure will also decrease to different extents. It is assumed that the technology coverage rate will reach 50% by 2035 and 80% by 2060.

Ruminant Rumen Regulation Simulation Scenario (LFADD): By adding methane inhibitors such as seaweed to the feed, the methane emissions in the enteric fermentation process of ruminants can be reduced by 50%. It is assumed that the technology coverage rate will reach 50% by 2035 and 80% by 2060.

Resource Utilization of Livestock and Poultry Manure Scenario (LWAST): This scenario strengthens manure resource utilization, substantially lowering methane and nitrous oxide. For example, using anaerobic microorganisms to ferment manure in an anaerobic environment to produce organic fertilizer or biogas can significantly reduce methane emissions. The anaerobic biogas fermentation technology can reduce the nitrous oxide emissions in the manure management process by 20% and methane emissions by 75%. Combined with the scale breeding proportion of different livestock species and the technology promotion progress, it is assumed that by 2035, the technology adoption rates for beef cattle, dairy cows, pigs, sheep, and poultry will be 30%, 70%, 60%, 30%, and 60%, respectively; by 2060, the technology adoption rates for beef cattle, dairy cows, pigs, sheep, and poultry will increase to 60%, 90%, 80%, 60%, and 80%, respectively.

Scenario of Replacing Red Meat with White Meat (LCONS): This scenario aligns with China's dietary guidelines recommending reduced red meat consumption in favor of white meat and aquatic products. The *Dietary Guidelines for Chinese Residents* points out that pork has a relatively high fat content, the saturated fatty acid content in poultry meat is relatively low, and aquatic products are rich in high-quality protein, lipids, vitamins, and minerals. Therefore, increasing the consumption of white meat and reducing the consumption of red meat is conducive to improving the health of residents. At present, in the meat consumption structure of Japan, the proportion of white meat consumption reaches 70%, and red meat only accounts for 30%. In the meat consumption of the United States and the European Union, the proportion of poultry meat consumption is relatively high, and the proportion of white meat consumption exceeds 50%. However, in China's meat consumption structure, pork consumption is dominant, and the proportion of red meat consumption is relatively high, exceeding 60%, and in some years, it exceeds 65%, while the proportion of white meat consumption is relatively low. Therefore, this study suggests that the meat consumption structure should be adjusted and optimized in the future. It is assumed that by 2035 and 2060, the consumption proportion of white meat will increase to 55% and 70%, respectively, which is equivalent to a reduction of about 30% in red meat consumption by 2035 and a reduction of 50% by 2060, with a corresponding increase in white meat consumption.

Comprehensive Emission Reduction Scenario in Livestock Industry (LCOMB): This integrated scenario combines all five aforementioned strategies to simulate their cumulative impact on livestock emissions.

Table 3-4 Design of Livestock Carbon Emission Reduction Simulation Scenarios

Scenarios	Content	Program	Adoption Rate
Benchmark (BASE)	business as usual		
Animal breeding (LPROD)	By increasing investment in scientific research funding for livestock breeding, animal productivity can be improved.	Productivity: 2035: +10% 2060: +30%	2035:30%; 2060:100%

Scenarios	Content	Program	Adoption Rate
Feed optimization (LFEED)	By using low-protein feed technology, feed conversion efficiency has been improved by 25%, and amino acid additives necessary for animals have been supplemented.	N_2O: Beef cattle: -25%; dairy cattle: -20%; pigs: -40%; sheep: -15%	2035:50%; 2060:80%
Ruminant rumen regulation (LFADD)	Use seaweed methane inhibitor additives to regulate intestinal fermentation in beef cattle, dairy cattle, and goats.	Intestinal CH_4: -50%	2035:50%; 2060:80%
Livestock manure resource utilization (LWAST)	Large-scale farms use anaerobic biogas fermentation technology to reduce CH_4 and N_2O emissions from manure.	Manure CH_4: -75%; N_2O:-20%	2035: Beef cattle 30%, dairy cattle 70%, pigs 60%, sheep 30%; 2060: Beef cattle 60%, dairy cattle 90%, pigs 80%, sheep 60%
Replacing red meat with white meat (LCONS)	Increase the proportion of white meat consumption and reduce the proportion of red meat consumption.	Proportion of white meat consumption: 2035: 55%; 2060: 70%	
Comprehensive emissions reduction (LCOMB)	Taking into account the above five proposals.		

Data source: Literatures and author estimates.

Benchmark Simulation Scenario (BASE): Under the BASE scenario, economic development and changing consumer preferences will shift China's dietary structure toward more beef, mutton, and poultry, while pork consumption stabilizes. To meet residents' consumption demands, livestock production will also undergo corresponding adjustments. The output of major agricultural products in 2060 is shown in Figure 3-5. Compared with 2025, by 2060, milk output will increase by 52%, followed by beef (25%), mutton (22%), while poultry (7%), eggs (7%), and pork (4%) will have limited growth space. Therefore, as output increases, livestock carbon emissions will rise with production growth, increasing from 487 million tonnes of carbon dioxide equivalent in 2021 to 567 million tonnes in 2035 and 636 million tonnes in 2060—representing increases of 16% and 30%, respectively. The main growth sources are beef and milk, which will together increase by nearly 100 million tonnes in 2060 compared to 2021.

Animal Breeding Simulation Scenario (LPROD): Compared with the benchmark scenario, the output of livestock and poultry meat (+25.74%), milk (+27.86%), and eggs (+20.84%) will significantly increase, along with feed consumption. The output of grains (+4.00%) and soybeans will also rise. Due to improved productivity and reduced carbon emission intensity, livestock carbon emissions in 2035 and 2060 will decrease by 10.16 million tonnes and 70 million tonnes, respectively—representing reductions of 1.8% and 11% compared to the BASE scenario. However, the increased feed production driven by enhanced livestock productivity will lead to higher carbon emissions from crops. Thus, carbon emissions from agricultural activities will decrease slightly less, by 9.34 million tonnes and 67.14 million tonnes.

Feed Optimization Simulation (LFEED): After improving feed conversion rates, reduced feed demand and lower production costs will encourage farmers to increase livestock production or output. Low-protein diet technology will reduce animals' demand for high-protein and high-energy feeds such as soybeans and corn, indirectly decreasing the cultivation of oilseeds and grains. The feed optimization scenario program has limited effects on reducing livestock carbon emissions itself—only decreasing by 4.25 million tonnes and 6.96 million tonnes in 2035 and 2060, respectively (about 1% reduction) compared to the BASE scenario. However, due to reduced feed consumption, crop carbon emissions will decline by 6.15 million tonnes and 9.82 million tonnes in 2035 and 2060, respectively.

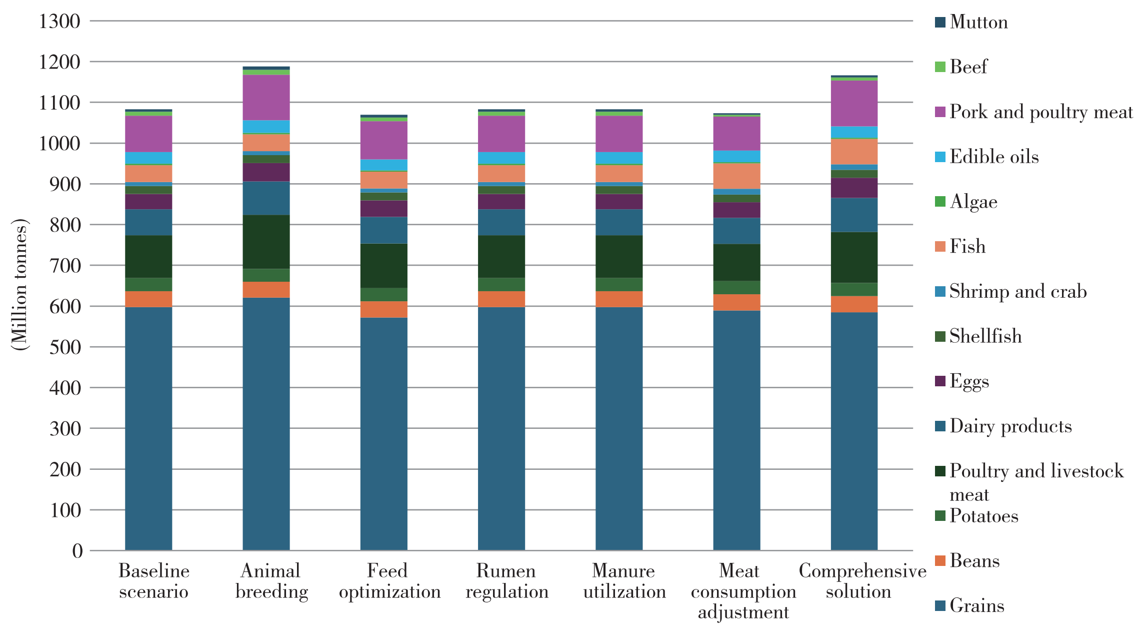
Ruminant Rumen Regulation Simulation (LFADD): Adding methane inhibitors can significantly reduce intestinal methane emissions. Compared to the BASE scenario, livestock carbon emissions will decrease by 88.37 million tonnes and 165 million tonnes in 2035 and 2060, respectively—representing declines of 15.6% and 25.9%.

Resource Utilization of Manure (LWAST): Using anaerobic microorganisms to ferment manure in an oxygen-free environment can significantly reduce nitrous oxide emissions from manure management. Compared to the BASE scenario, total livestock carbon emissions will decrease by 61.23 million tonnes and 87.75 million tonnes in 2035 and 2060, respectively—representing reductions of 10.8% and 13.8%.

Meat Consumption Structure Optimization (LCONS): Adjusting the meat consumption structure at the demand side, increasing white meat consumption and reducing red meat consumption, can also significantly reduce carbon emissions. Compared to the BASE scenario, carbon emissions will decrease by 120 million tonnes and 230 million tonnes in 2035 and 2060, respectively—representing declines of 21.8% and 36.3%.

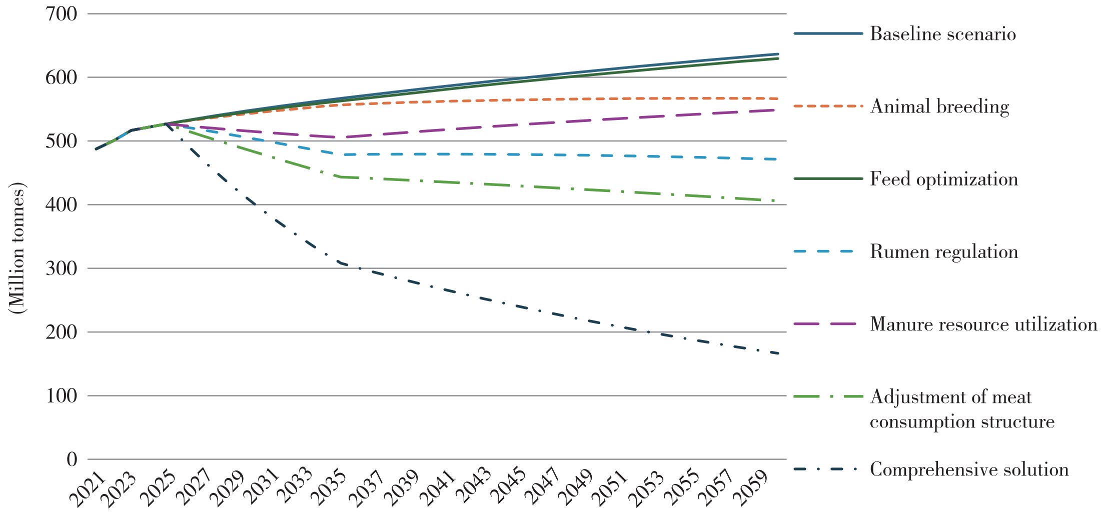
Comprehensive Emission Reduction Scenario (LCOMB): By comprehensively implementing the above five emission reduction measures, livestock carbon emissions will be significantly reduced. In 2035 and 2060, livestock carbon emissions will drop to 308 million tonnes and 166 million tonnes, respectively—decreasing by 269 million tonnes and 470 million tonnes of COmpared to the BASE scenario, with reduction rates as high as 45.7% and 73.9%.

Figure 3-5 Major agricultural production under different scenarios in 2060



Source: CAU-AFS model results.

Figure 3-6 Future carbon emissions from livestock industry in China under various simulation scenarios



Source: CAU-AFS model results.

Each mitigation measure contributes to reducing livestock carbon emissions, with effects intensifying over time. Among them, rumen regulation and manure resource utilization have notable emission reduction potential. Importantly, adjusting the meat consumption structure is a crucial pathway for demand-side mitigation, which can substantially decrease livestock carbon emissions. However, the impact of any single measure is limited. Only by integrating various supply- and demand-side interventions can reduce livestock carbon emissions more substantially.

3.5 Policy Recommendations for Low-carbon Transition in the Livestock Industry

China's livestock industry accounts for substantial and diverse sources of carbon emissions, particularly as consumer demand for high-emission products like beef and mutton continues to grow. This underscores the sector's significant potential for low-carbon transformation. Based on an analysis of current livestock demand and carbon emission patterns in China, the following key findings emerge: First, the primary sources of carbon emissions in China's livestock sector are enteric fermentation and manure management, with energy consumption contributing a smaller proportion. Cattle, pigs, and sheep are the main carbon-emitting livestock species. Aside from enteric fermentation, manure, and energy-related emission reduction measures, integrated strategies like breed selection, feed optimization, pasture management, and demand-side substitution are vital pathways. Second, exogenous additives represented by methane inhibitor, feed and manure management, and biogas utilization demonstrate significant emission reduction potential and economic feasibility. Meanwhile, technologies such as seaweed-based additives, clean energy sources like photovoltaic power, and alternative proteins require further R&D and cost control. Third, non-standard operations in emission reduction may have disadvantage effects in food production, farmers' income, and even cause land and water pollution. Therefore, selecting such pathways requires comprehensive assessment of combined environmental and economic impacts.

To facilitate a low-carbon transition, this chapter proposes the improvement on six aspects: improving carbon emission monitoring, fostering technological innovation, enhancing crop-livestock circulation, optimizing consumption structure of animal products, stimulating market construction and improvement, and reforming policy support, so as to explore the feasible paths and practices for the low-carbon transformation of livestock industry.

1. Strengthen Carbon Emissions Monitoring to Support Evidence-based Action

The agricultural authorities should promote the advancement of carbon emission monitoring technologies in the livestock sector and establish a comprehensive database to facilitate evidence-based emission reduction strategies. Specifically, efforts should focus on refining and standardizing the carbon emission monitoring indicators, determining key parameters, optimizing the accounting methods, establishing a localized emission factor database, and promoting the mutual recognition and coordination of international standards to improve the accuracy and comparability of accounting. The industry association should implement systematic monitoring of enteric fermentation and manure management processes, while expediting the integration of intelligent and information technologies in critical emission reduction areas. Real-time and precise emission monitoring should be implemented through advanced sensor networks and remote sensing technologies, which helps to utilize big data analytics to enhance data acquisition and processing efficiency. This will establish a reliable foundation for carbon emission supervisition and mitigation in the livestock sector.

2. Advance Technological Innovation to Achieve Low-carbon, High-Efficiency Production

Green and low-carbon cutting-edge technologies need to be advanced to achieve synergistic increase in production and efficiency with low-carbon emission reduction. The research priorities should emphasize low-carbon breeding initiatives, including: developing superior low-carbon varieties through selective breeding programs; applying genetic technologies to enhance feed conversion efficiency while reducing carbon emissions; and intensifying R&D on novel low-carbon feed additives, particularly methane inhibitors and microalgae-based supplements. It is crucial to accelerate the R&D progress of feed processing and optimization management and alternative proteins, gradually shift from in vitro testing to in vivo testing, avoid the adverse impact of related technologies on product yield and environmental pollution, and break the environmental protection trade barriers of animal products.

The livestock sector shall stimulate the innovation of renewable energy and low-carbon technologies, use alternative energy sources such as solar energy and wind energy, combine the application of alternative energy sources with the actual animal-farming and strengthen the investment in livestock sector. The livestock sector should prioritize innovation in renewable energy and low-carbon technologies by: (1) deploying alternative energy sources (e.g., solar, wind) in integrated farming systems; (2) increasing investment in livestock manure resource recovery technologies; and (3) developing cost-effective facility-based solutions for enhanced emission reduction.

The livestock producers must make full use of advanced equipment and technology to achieve precise feeding, control the feeding amount and nutritional components, apply intelligent breeding technology, and develop herd management benchmark tools such as mobile phone applications (Michels et al., 2019; Warner et al., 2020). Instruments include using the Internet, big data, artificial intelligence and other technologies to continuously detect the status of the herd, and reasonably feed according to the needs of livestock and poultry at different stages and status, which can optimize the breeding process and improve feed utilization rate.

3. Promote Circular Agriculture by Integrating Crop and Livestock Systems

A circular and sustainable path can be built through ecological livestock farming. The livestock farms need to closely combine livestock and poultry farming with crop planting, use livestock and poultry manure to return to the field as a nutrient source, and the crops and straws produced are used as forage sources for livestock and poultry. The producters should optimize the variety and scale of livestock and poultry, while reducing the carbon emissions from the input of chemical fertilizers and other agricultural materials and the transportation and processing of feed. These measures can help to reduce agricultural non-point source pollution, and improve the self-regulation ability of the agricultural ecosystem to achieve nutrient and resource circulation.

At the same time, the development of ecological circular animal husbandry needs to reasonably select the combination mode of planting and livestock-farming considering the herd scale and regional reality. It is essential to increase the nutrient management and operation mechanism innovation, and build and form a long-term mechanism for planting and livestock-farming circulation through the interest chain mechanism, manure subsidy and payment (Wang et al., 2024). The livestock sector should explore the circular development system of planting and livestock-farming such as grass-livestock balance and forestry-animal husbandry combination, aiming to achieve both the ecological and economic goals (Zhang, 2025).

4. Encourage Dietary Shifts to Align Consumption with Low-carbon Goals

The community should advocate a balanced diet and drive the optimization of consumption structure. The nutrition and health authorities should enhance public education on nutrition, health, and green low-carbon principles by: (1) promoting dietary guidelines incorporating carbon reduction objectives; (2) disseminating scientific dietary knowledge; and (3) utilizing digital media platforms to guide consumers toward adopting healthier and more environmentally sustainable dietary patterns and consumption behaviors. It calls consumers to moderately reduce the intake of red meat (mainly pork), increase the intake proportion of high-quality proteins such as poultry (such as chicken), and reasonably adjust the dietary structure. On the one hand, the balanced diets can reduce the risk of health diseases such as dementia, cognitive impairment and cancer (Shanmugam et al., 2024; Li et al., 2025). On the other hand, replacing high-carbon red meat with low-carbon poultry meat can achieve the goal of carbon control and reduction through the optimization of the food structure. These actions can drive the upgrading of the livestock industry structure with the change of demand at the consumption end, reduce the scale of high-carbon livestock at the production end, then effectively force the overall low-carbon transformation of livestock industry.

5. Establish Livestock Carbon Markets to Incentivize Emission Reduction

The low-carbon transition of the livestock industry calls to explore carbon market transactions and promote carbon reduction circulation with system construction. The government should accelerate the standardization construction of carbon accounting systems for animal husbandry, large-scale breeding enterprises and small and medium-sized farms, joint with third-party institutions to establish a sound carbon emission monitoring and management system. The livestock industry and associations should reasonably allocate carbon emission indicators, clarify emission reduction quotas, trading rules and trading prices, and ensure the transparency, fairness and authenticity of carbon trading, so as to guide the adoption and application upgrading of breeding emission reduction technologies. The government departments should lead in launching carbon trading pilots in some regions or production areas of specific livestock and poultry products, and encourage livestock producers to participate in carbon trading. It is crucial to innovate incentive measures such as tax reduction, rewards and subsidies for those with significant emission reduction effects, increase the enthusiasm of farmers and others to participate, and punish over-emitting enterprises. At the same time, the supporting financial system should develop the carbon financial mechanism, use financial tools such as investment and loans to provide financing support and economic guarantee for low-carbon project construction and transaction projects, and actively promote cooperation with international organizations and financial institutions. It is highly cost-effective to work with the global community to stimulate the formation of the international animal husbandry carbon sink market and the formulation of international uniform standards for carbon trading, as well as establish corresponding certification and supervision mechanisms to ensure the authenticity and sustainability of transaction projects.

6. Enhance Policy Design to Guide and Accelerate the Transition

Policy support should be improved to guide the low-carbon development of livestock industry with precision and foresight. On the one hand, actions call to optimize the regional layout by strengthening the cooperation and exchange between major livestock industry provinces and surrounding economically strong provinces to jointly formulate goals and action plans, which are based on their resource endowments and environmental carrying capacity. These actions can help to optimize the production layout of the livestock industry, and drive the realization of economic and ecological benefits of the region with technological R&D and promotion, surrounding market development and upstream and downstream integration. On the other hand, policies are encouraged to incline towards the R&D and construction of low-carbon technologies, encourage enterprises, especially private enterprises, to make innovation attempts. It demands to set up special support funds and give tax relief to relevant enterprises engaged in low-carbon technology R&D, equipment construction and product production. Government agencies should conduct forward-looking industry assessments, develop comprehensive sectoral development plans, and provide strategic guidance to livestock producers for proactive operational planning. The efforts call to set up demonstration enterprises in batches, fund internal personnel breeding training of enterprises, strengthen cooperation with universities and scientific research institutions, and enhance the construction of low-carbon transformation think tanks and projects. At the same time, the transformation requires to create a low-carbon product business mode at the consumption end. It is of great importance to explore the brand construction of low-carbon livestock and poultry products, guide consumers' green premium cognition, and enhance the combination mode of animal husbandry culture and tourism.

These six pathways jointly establish a strategic framework to facilitate China's livestock sector transition to enhanced sustainability and lower carbon emissions, while maintaining equilibrium among production efficiency, ecological sustainability, and economic viability.

References

Abbott D W, Aasen I M, Beauchemin K A, et al. Seaweed and seaweed bioactives for mitigation of enteric methane: challenges and opportunities[J]. Animals, 2020, 10(12): 2432.

Aboagye I A, Beauchemin K A. Potential of molecular weight and structure of tannins to reduce methane emissions from ruminants: A review[J]. Animals, 2019, 9(11): 856.

AGFEP, CARD, CIFAE, et al. 2021 China and global food policy report[R]. 2021.

Almeida A K, Hegarty R S, Cowie A. Meta-analysis quantifying the potential of dietary additives and rumen modifiers for methane mitigation in ruminant production systems[J]. Animal Nutrition, 2021, 7(4): 1219-1230.

Alvarez-Hess P S, Little S M, Moate P J, et al. A partial life cycle assessment of the greenhouse gas mitigation potential of feeding 3-nitrooxypropanol and nitrate to cattle[J]. Agricultural systems, 2019, 169: 14-23.

Auclair O, Eustachio C P, Milner J, et al. Partial substitutions of animal with plant protein foods in Canadian diets have synergies and trade-offs among nutrition, health and climate outcomes[J]. Nature Food, 2024, 5(2): 148-157.

Bai Y F, Guo C C, Li S S, et al. Instability of decoupling livestock greenhouse gas emissions from economic growth in livestock products in the Tibetan highland[J]. Journal of Environmental Management, 2021, 287: 112334.

Bateki C A, Wassie S E, Wilkes A. The contribution of livestock to climate change mitigation: A perspective from a low-income country[J]. Carbon Management, 2023, 14(1): 1-16.

Bature I, Wu X H, Ding X. The roles of phytogenic feed additives, trees, shrubs, and forages on mitigating ruminant methane emission[J]. Frontiers in Veterinary Science, 2024, 11: 1475322.

Beauchemin K A, McGinn S M, Benchaar C, et al. Crushed sunflower, flax, or canola seeds in lactating dairy cow diets: Effects on methane production, rumen fermentation, and milk production[J]. Journal of dairy science, 2009, 92(5): 2118-2127.

Belanche A, Newbold C J, Morgavi D P, et al. A meta-analysis describing the effects of the essential oils blend agolin ruminant on performance, rumen fermentation and methane emissions in dairy cows[J]. Animals, 2020, 10(4): 620.

Bijl R, et al. Impact of robotic milking on dairy farm efficiency[J]. Journal of Dairy Science, 2017, 100(9), 7729-7738.

Bokma S, Hogeveen H. Optimization of dairy cattle replacement while lowering environmental emissions and excretions[J]. 2024.

Brito A F, Almeida K V, Oliveira A S. Production performance, nutrient use efficiency, and predicted enteric methane emissions in dairy cows under confinement or grazing management system[J]. Translational Animal Science, 2022, 6(2): txac028.

Brito L F, Bedere N, Douhard F, et al. Review: Genetic selection of high-yielding dairy cattle toward sustainable farming systems in a rapidly changing world. Animal. 2021, 15:100292.

Bruun S, Jensen L S, Sommer S. Small-scale household biogas digesters: An option for global warming mitigation or a potential climate bomb?[J]. Renewable and Sustainable Energy Reviews, 2014, 33: 736-741.

Cao Y B, Wang X, Liu L, et al. Acidification of manure reduces gaseous emissions and nutrient losses from subsequent composting process[J]. Journal of Environmental Management, 2020, 264: 110454.

Chen F F, Zhang C S, Wang Y N, et al. Patterns and cost-benefit analysis of manure disposal of scale pig production in China[J]. China Environmental Science, 2017, 37(9): 3455-3463.

China Council for International Cooperation on Environment and Development. Building an inclusive green and low-carbon economy[R]. 2023.

Clemens J, Trimborn M, Weiland P, et al. Mitigation of greenhouse gas emissions by anaerobic digestion of cattle slurry. Agriculture, Ecosystems & Environment, 2006, 112(2-3), 171-177.

Collett K, O'Callaghan B, Mason M, et al. The climate impact of alternative proteins[J]. Smith School Final 25% Series Paper, 2021.

Congio G F S, Bannink A, Mogollón O L M, et al. Enteric methane mitigation strategies for ruminant livestock systems in the Latin America and Caribbean region: A meta-analysis[J]. Journal of Cleaner Production, 2021, 312: 127693.

Congio G F S, Batalha C D A, Chiavegato M B, et al. Strategic grazing management towards sustainable intensification at tropical pasture-based dairy systems[J]. Science of The Total Environment, 2018, 636: 872-880.

Dai X W, Li J H, He Y Q, et al. Regional equity and efficiency of carbon emissions of China's livestock industry in 2000-2020[J]. Resources Science, 2023, 45(1): 62-76.

Dalby F R, Guldberg L B, Feilberg A, et al. Reducing greenhouse gas emissions from pig slurry by acidification with organic and inorganic acids[J]. PLoS One, 2022, 17(5): e0267693.

Davis K F, Gephart J A, Emery K A, et al. Meeting future food demand with current agricultural resources[J]. Global Environmental Change, 2016, 39: 125-132.

De Haas Y, Veerkamp R F, De Jong G, et al. Selective breeding as a mitigation tool for methane emissions from dairy cattle[J]. Animal, 2021, 15: 100294.

Du R R, He T, Khan A, et al. Carbon emissions changes of animal husbandry in China: Trends, attributions, and solutions: A spatial shift-share analysis[J]. Science of The Total Environment, 2024, 929: 172490.

Elahi E, Weijun C, Jha S K, et al. Estimation of realistic renewable and non-renewable energy use targets for livestock production systems utilising an artificial neural network method: A step towards livestock sustainability[J]. Energy, 2019, 183: 191-204.

Elshimy M, El-Aasar K M. Carbon footprint, renewable energy, non-renewable energy, and livestock: testing the environmental Kuznets curve hypothesis for the Arab world[J]. Environment, Development and Sustainability, 2020, 22(7): 6985-7012.

Fang Q C, Zhang X Y, Dai G C, et al. Low-opportunity-cost feed can reduce land-use-related environmental impacts by about one-third in China[J]. Nature food, 2023, 4(8): 677-685.

Gan Y T. Research on the estimation and influence factors of carbon emission of dairy cattle industry in China[D]. Northeast Agricultural University, 2019.

Gerber P J, Steinfeld H, Henderson B, et al. Tackling climate change through livestock: a global assessment of emissions and mitigation opportunities[M]. 2013.

Gerber P, Vellinga T, Opio C, et al. Productivity gains and greenhouse gas emissions intensity in dairy systems[J]. Livestock science, 2011, 139(1-2): 100-108.

Gislon G, Colombini S, Borreani G, et al. Milk production, methane emissions, nitrogen, and energy balance of cows fed diets based on different forage systems[J]. Journal of Dairy Science, 2020, 103(9): 8048-8061.

Goopy J P. Creating a low enteric methane emission ruminant: what is the evidence of success to the present and prospects for developing economies?[J]. Animal Production Science, 2019, 59(10): 1769-1776.

Govoni C, D' Odorico P, Pinotti L, et al. Preserving global land and water resources through the replacement of livestock feed crops with agricultural by-products[J]. Nature Food, 2023, 4(12): 1047-1057.

Guo Y, et al. Yeast culture supplementation alters rumen microbial communities and reduces methane emission in dairy cows[J]. Journal of Dairy Science, 2020, 103(9), 8044-8055.

Haas Y D, Veerkamp R F, Jong G D, et al. Selective breeding as a mitigation tool for methane emissions from dairy cattle[J]. Animal, 2021, 15: 100294.

Han Y Q. The impact of China's dairy industrialization on greenhouse gas emissions and the potential for emission mitigation[D]. Shandong Normal University, 2024.

Hardie C A, Wattiaux M, Dutreuil M, et al. Feeding strategies on certified organic dairy farms in Wisconsin and their effect on milk production and income over feed costs[J]. Journal of dairy science, 2014, 97(7): 4612-4623.

Harrison M T, Cullen B R, Mayberry D E, et al. Carbon myopia: The urgent need for integrated social, economic and environmental action in the livestock sector[J]. Global Change Biology, 2021, 27(22): 5726-5761.

Hassanat F, Gervais R, Julien C, et al. Replacing alfalfa silage with corn silage in dairy cow diets: Effects on enteric methane production, ruminal fermentation, digestion, N balance, and milk production[J]. Journal of Dairy Science, 2013, 96(7): 4553-4567.

He D W, Deng X Z, Wang X S, et al. Livestock greenhouse gas emission and mitigation potential in China[J]. Journal of Environmental Management, 2023, 348: 119494.

Hodge I, Quille P, O' Connell S. A Review of Potential Feed Additives Intended for Carbon Footprint Reduction through Methane Abatement in Dairy Cattle[J]. Animals, 2024, 14(4): 568.

Holly M A, Larson R A, Powell J M, et al. Greenhouse gas and ammonia emissions from digested and separated dairy manure during storage and after land application[J]. Agriculture, Ecosystems & Environment, 2017, 239: 410-419.

Hou, Y, et al. Smart manure management for carbon neutrality[J]. Environmental Science & Technology, 2022, 56(8), 4875-4886.

Hristov A N, et al. Mitigation of greenhouse gas emissions in livestock production[M]. FAO Animal Production and Health Paper, 2013, 177.

Hristov A N, Oh J, Giallongo F, et al. An inhibitor persistently decreased enteric methane emission from dairy cows with no negative effect on milk production[J]. Proceedings of the national academy of sciences, 2015, 112(34): 10663-10668.

Huang H, Wang X, Luo Y S, et al. Enrichment, influencing factors and applications of heavy metals by macroalgae[J]. Journal of Shanghai Ocean University, 2022, 31(5): 1158-1167.

Jayanegara A, et al. Meta-analysis of methane mitigation by tannin-rich feed additives in ruminants[J]. Animal Feed Science and Technology, 2012, 176(1-4), 72-79.

Jia P, Tu Y, Liu Z H, et al. Diets supplementation with Bacillus subtilis and Macleaya cordata extract improve production performance and the metabolism of energy and nitrogen, while reduce enteric methane emissions in dairy cows[J]. Animal Feed Science and Technology, 2022, 294: 115481.

Jiang T, Wen Z G, Ma X G, et al. Characteristics and efficiency evaluation of livestock slurry separation technologies[J]. Transactions of the Chinese Society of Agricultural Engineering, 2016, 32(Supp.2): 218-225.

Jiao H P, Dale A J, Carson A F, et al. Effect of concentrate feed level on methane emissions from grazing dairy cows[J]. Journal of Dairy Science, 2014, 97(11): 7043-7053.

Knapp J R, Laur G L, Vadas P A, et al. Invited review: Enteric methane in dairy cattle production: Quantifying the opportunities and impact of reducing emissions[J]. Journal of dairy science, 2014, 97(6): 3231-3261.

Kolling G J, Stivanin S C B, Gabbi A M, et al. Performance and methane emissions in dairy cows fed oregano and green tea extracts as feed additives[J]. Journal of Dairy Science, 2018, 101(5): 4221-4234.

Kulshreshtha G, Hincke M T, Prithiviraj B, et al. A review of the varied uses of macroalgae as dietary supplements in selected poultry with special reference to laying hen and broiler chickens[J]. Journal of Marine Science and Engineering, 2020, 8(7): 536.

Lahart B, Shalloo L, Herron J, et al. Greenhouse gas emissions and nitrogen efficiency of dairy cows of divergent economic breeding index under seasonal pasture-based management[J]. Journal of Dairy Science, 2021, 104(7): 8039-8049.

Lauer M, Hansen J K, Lamers P, et al. Making money from waste: The economic viability of producing biogas and biomethane in the Idaho dairy industry[J]. Applied Energy, 2018, 222: 621-636.

Lee B H. Fundamentals of food biotechnology[M]. John Wiley & Sons, 2014.

Lei M, Cheng Y Z, Miao N, et al. Effects of mixing loess and other additives with pig manure on ammonia and greenhouse gas emissions during storage[J]. Acta Scientiae Circumstantiae, 2019, 39(12): 4132-4139.

Li C H, Pradhan P, Wu X D, et al. Livestock sector can threaten planetary boundaries without regionally differentiated strategies[J]. Journal of Environmental Management, 2024, 370: 122444.

Li E Q, Hou Y P, Han J, et al. Optimization planning of multi-energy coupling system for livestock farms considering the optimization of solar-biogas combination mode[J]. Distribution & Utilization, 2023, 40(01): 33-40+55.

Li F, Cheng S K, Yu H L, et al. Waste from livestock and poultry breeding and its potential assessment of biogas energy in rural China[J]. Journal of Cleaner Production, 2016, 126: 451-460.

Li J H, Yang G J, Pei X D, et al. Research into the spatial and temporal changes in patterns of animal husbandry-related CO_2 emission intensities and the factors influencing those emissions in Qinghai Province. Acta Prataculturae Sinica, 2025, 34(3): 1-16.

Li J Y, Liu Z F, Dai Y D, et al. Research progress of low-protein diet regulating production performance and enteric methane emissions of ruminants[J]. Feed Industry, 2024, 45(13): 47-52.

Li J, Pan L S. Main contradictions and solutions to the high-quality development of animal husbandry under the background of rural revitalization[J]. Economic Review Journal, 2022, (08): 58-64.

Li R T, Song G H, Li J, et al. The status quo and problems of resource utilization of livestock manure[J]. Acta Ecologiae Animalis Domastici, 2022, 7: 83-87.

Li S W, Zhang M X, Hou L L, et al. A framework for cost-effectiveness analysis of greenhouse gas mitigation measures in dairy industry with an application to dairy farms in China[J]. Journal of Environmental Management, 2024, 370: 122521.

Li Y H, Li Y P, Gu X, et al. Long-term intake of red meat in relation to dementia risk and cognitive function in US adults[J]. Neurology, 2025, 104(3): e210286.

Li Z Z, Liu L, Ma L, et al. Impact of aquatic product trade on land use, carbon emissions and biodiversity[J]. Chinese Journal of Eco-Agriculture, 2023, 31(8): 1301-1310.

Liang D, Cabrera V E. Optimizing productivity, herd structure, environmental performance, and profitability of dairy cattle herds[J]. Journal of Dairy Science, 2015, 98(4): 2812-2823.

Liu M R, Mao Y W, Luo X, et al. Research progress on materials and technologies of plant-based meat[J]. Food and Fermentation Industries, 2021, 47(4): 293-298.

Løvendahl P, Difford G F, Li B, et al. Selecting for improved feed efficiency and reduced methane emissions in dairy cattle[J]. Animal, 2018, 12(s2): s336-s349.

Luo J, Zhao L X, Yao Z L, et al. Construction and application of comprehensive evaluation index system for waste treatment on intensive livestock farms[J]. Transactions of the Chinese Society of Agricultural Engineering, 2020, 36(17): 182-189.

Ma C, Dalby F R, Feilberg A, et al. Low-dose acidification as a methane mitigation strategy for manure management[J]. ACS Agricultural Science & Technology, 2022, 2(3): 437-442.

Ma R Y, Xiao H F. Livestock industry carbon emissions in China: Connotation characteristics, research progress and prospective implications[J]. Journal of China Agricultural University, 2024, 29(12): 185-195.

Ma Y Q, Cao D G, Luo W H, et al. The evaluation of the livestock and poultry production of carbon emissions in China based on life cycle assessment[J]. China Environmental Science, 2024, 44(5): 2799-2810.

Macome F M, Pellikaan W F, Hendriks W H, et al. In vitro gas and methane production in rumen fluid from dairy cows fed grass silages differing in plant maturity, compared to in vivo data[J]. Journal of Animal Physiology and Animal Nutrition, 2018, 102(4): 843-852.

Maia A S C, de Andrade C E, Fonsêca V F C, et al. Photovoltaic panels as shading resources for livestock[J]. Journal of Cleaner Production, 2020, 258: 120551.

Makkar H P S. Feed demand landscape and implications of food-not feed strategy for food security and climate change[J]. Animal, 2018, 12(8): 1744-1754.

Michels M, Bonke V, Musshoff O. Understanding the adoption of smartphone apps in dairy herd management[J]. Journal of dairy science, 2019, 102(10): 9422-9434.

Ministry of Ecology and Environment of the People's Republic of China. The First Biennial Transparency Report on Climate Change of the People's Republic of China [R]. 2024.

Minoofar A, Gholami A, Eslami S, et al. Renewable energy system opportunities: A sustainable solution toward cleaner production and reducing carbon footprint of large-scale dairy farms[J]. Energy Conversion and Management, 2023, 293: 117554.

Moate P J, Williams S R O, Deighton M H, et al. Effects of feeding wheat or corn and of rumen fistulation on milk production and methane emissions of dairy cows[J]. Animal Production Science, 2018, 59(5): 891-905.

Monteny G J, Bannink A, Chadwick D. Greenhouse gas abatement strategies for animal husbandry[J]. Agriculture, Ecosystems & Environment, 2006, 112(2-3): 163-170.

Neethirajan S. The role of sensors, big data and machine learning in modern animal farming[J]. Sensing and Bio-Sensing Research, 2020, 29: 100367.

Nijdam D, Rood T, Westhoek H. The price of protein: Review of land use and carbon footprints from life cycle assessments of animal food products and their substitutes[J]. Food policy, 2012, 37(6): 760-770.

Ólafsdóttir S S, Jensen C D, Lymperatou A, et al. Effects of different treatments of manure on mitigating methane emissions during storage and preserving the methane potential for anaerobic digestion[J]. Journal of Environmental Management, 2023, 325: 116456.

Ondarza D B M, Souza D C V, Kebreab E, et al. Understanding potential opportunities and risks associated with feeding supplemental rumen available fats to mitigate enteric methane emissions in lactating dairy cows[J]. Journal of Dairy Science, 2024, 107(10):8072-8083.

O'Sullivan M, Shalloo L, Pierce K M, et al. Economic assessment of Holstein-Friesian dairy cows of divergent Economic Breeding Index evaluated under seasonal calving pasture-based management[J]. Journal of Dairy Science, 2020, 103(11): 10311-10320.

Pang J W. Research on the investment risk management of pastoral and optical complementary project under PPP model - take Zhanjiang A Project as an example[D]. South China University of Technology, 2023.

Petersen S O, Blanchard M, Chadwick D, et al. Manure management for greenhouse gas mitigation[J]. Animal, 2013, 7(s2): 266-282.

Pittaluga A M, Yang F, Gaffney J R, et al. Effect of supplementation with ruminal probiotics on growth performance, carcass characteristics, plasma metabolites, methane emissions, and the associated rumen microbiome changes in beef cattle[J]. Journal of Animal Science, 2023, 101: skac308.

Poore J, Nemecek T, Reducing food's environmental impacts through producers and consumers[J]. Science, 2018, 360(6392): 987-992.

Qiao S Y, Zhou J Y, Li S J, et al. Diversified diet with low protein and low soybean meal is a key technology for pigs industry to save feed and improve efficiency[J]. Chinese Journal of Animal Nutrition, 2024, 36(06): 3401-3412.

Qiao S Y. Research and Application of Low-Protein Diets for Pigs[M]. Beijing: China Agriculture Press, 2000.

Qin S P, Li T, Zhang Y J, et al. Calculation of non-CO_2 greenhouse gas emissions from Chinese agricultural sources. Acta Ecologica Sinica, 2024, 44(17): 7536-7551

Rotz C A, et al. Environmental impacts of livestock production systems[J]. Agricultural Systems, 2019, 176, 102644.

Sakadevan K, Nguyen M L. Livestock production and its impact on nutrient pollution and greenhouse gas emissions[J]. Advances in agronomy, 2017, 141: 147-184.

Sarttra T, Kittitanasak K, Wongwaitayakul K, et al. An optimal approach for supply and demand management with the consideration of cattle herd structure management: A case study of medium-size dairy cooperative in Thailand[J]. Computers & Industrial Engineering, 2023, 182: 109355.

Savian J V, Schons R M T, Marchi D E, et al. Rotatinuous stocking: A grazing management innovation that has high potential to mitigate methane emissions by sheep[J]. Journal of Cleaner Production, 2018, 186: 602-608.

Schader C, Muller A, Scialabba N E H, et al. Impacts of feeding less food-competing feedstuffs to livestock on global food system sustainability[J]. Journal of the Royal Society Interface, 2015, 12(113): 20150891.

Shanmugam R, Majee P, Shi W, et al. Iron-(Fe^{3+})-Dependent Reactivation of Telomerase Drives Colorectal Cancers[J]. Cancer Discovery, 2024, 14(10): 1940-1963.

Shao G X. The era value, realistic basis and improvement path of green development of animal husbandry in the context of Chinese modernization[J]. Feed Industry, 2024, 45(06): 130-133.

Shen R M, Cai F F, Song C, et al. Research progress in biochar-enhanced anaerobic digestion[J]. Journal of Beijing University of Chemical Technology (Natural Science), 2022, 49(6): 1-13.

Shi R B, Irfan M, Liu G L, et al. Analysis of the impact of livestock structure on carbon emissions of animal husbandry: a sustainable way to improving public health and green environment[J]. Frontiers in Public Health, 2022, 10: 835210.

Sokolov V K, VanderZaag A, Habtewold J, et al. Dairy manure acidification reduces CH4 emissions over short and long-term[J]. Environmental Technology, 2021, 42(18): 2797-2804.

Sokolov V, VanderZaag A, Habtewold J, et al. Greenhouse gas mitigation through dairy manure acidification[J]. Journal of Environmental Quality, 2019, 48(5): 1435-1443.

Soosten D V, Meyer U, Flachowsky G, et al. Dairy cow health and greenhouse gas emission intensity[J]. Dairy, 2020, 1(1): 20-29.

Stefenoni H A, Räisänen S E, Cueva S F, et al. Effects of the macroalga Asparagopsis taxiformis and oregano leaves on methane emission, rumen fermentation, and lactational performance of dairy cows[J]. Journal of Dairy Science, 2021, 104(4): 4157-4173.

Sun Y, Li S, Tan S, et al. The Application of Macroalgae in Ruminant Production[J]. China Animal Husbandry & Veterinary Medicine, 2024, 51(06): 2440-2450.

Tan Z, et al. Tea saponin reduces methane emission by selectively inhibiting methanogens in goats[J]. Animal Nutrition, 2021, 7(2), 420-428.

Tian C S, Chen Y. China's provincial agricultural carbon emissions measurement and low carbonization level evaluation: Based on the application of derivative indicators and TOPSIS [J]. Journal of Natural Resources, 2021, 36(2): 395-410.

Tian Y, Xia R, Li B. Re-evaluation of China's animal husbandry carbon emission: Current characteristics, dynamic evolution, and spatial correlation [J]. China Environmental Science, 2025, 45(3):1686-1698.

Tian Y, Yin M H. Re-evaluation of China's agricultural carbon emissions: Basic status, dynamic evolution and spatial spillover effects[J]. Chinese Rural Economy, 2022, (03):104-127.

Tong B X, Zhang L, Hou Y, et al. Lower pork consumption and technological change in feed production can reduce the pork supply chain environmental footprint in China[J]. Nature Food, 2023, 4(1): 74-83.

Tricarico J M, Kebreab E, Wattiaux M A. MILK Symposium review: Sustainability of dairy production and consumption in low-income countries with emphasis on productivity and environmental impact[J]. Journal of dairy science, 2020, 103(11): 9791-9802.

Van Zijderveld, S M, et al. Nitrate supplementation reduces methane emission in dairy cows[J]. Journal of Dairy Science, 2011, 94(6), 3171-3180.

Wanapat M, Prachumchai R, Dagaew G, et al. Potential use of seaweed as a dietary supplement to mitigate enteric methane emission in ruminants[J]. Science of The Total Environment, 2024: 173015.

Wang B, Yu L J, Fu X F, et al. Research on reducing methane emissions by optimizing breeding in sheep[J]. Grass-Feeding Livestock, 2019, (03): 1-5.

Wang F Z, Li C X, Cui L H. Study on the spatiotemporal evolution characteristics and spillover effects of carbon emission efficiency in China's livestock industry[J]. Ecological Economy, 2025, 41(01):158-167.

Wang G L, Zhang W, Liang J Y, et al. Evaluation of geothermal resources potential in China[J]. Acta Geosci-

entica Sinica, 2017, 38(04): 449-450+134+451-459.
Wang H G, Zhang L, Wang X, et al. Life cycle assessment of ammonia and methane emission reduction techno-logy model for manure management in Hebei Province[J]. Chinese Journal of Eco-Agriculture, 2024, 32(6): 1054-1062.
Wang J, Zhang H, Shen Y J, et al. Development practice and promotion route of circular agriculture in China[J]. Transactions of the Chinese Society of Agricultural Engineering, 2024, 40(22): 12-21.
Wang Y, Wang Y, Wu C Y, et al. Comprehensive evaluation research of livestock and poultry waste treatment technologies in the ecological fragile areas of Northwest China[J]. Journal of Environmental Engineering Technology, 2023, 13(2): 654-662.
Wang Y, Zhou J, Wang G, et al. Advances in low-protein diets for swine[J]. Journal of animal science and biotechnology, 2018, 9: 1-14.
Wang Y, Zhu Z P, Dong H M, et al. Mitigation potential of methane emissions in China's livestock sector can reach one-third by 2030 at low cost[J]. Nature Food, 2024, 5(7): 603-614.
Warner D, Vasseur E, Villettaz R M, et al. Development of a benchmarking tool for dairy herd management using routinely collected herd records[J]. Animals, 2020, 10(9): 1689.
Wei C B, Sha Y Y, Hou Y W, et al. Spatial-Temporal Evolution and Influencing Factors of Animal Husbandry Carbon Emissions: A Case Study of Shandong Province, China[J]. Sustainability, 2024, 16(9): 3640.
Wei S, Fan J M, Tian Y F, et al. Low-carbon development policies and achievements in the context of the livestock sector in China[J]. Frontiers of Agricultural Science & Engineering, 2024, 11(3).
Weiby K V, Krizsan S J, Eknæs M, et al. Associations among nutrient concentration, silage fermentation products, in vivo organic matter digestibility, rumen fermentation and in vitro methane yield in 78 grass silages[J]. Animal Feed Science and Technology, 2022, 285: 115249.
Wu Q, Zhang Y Y, Zhang M Y. Quantitative assessment, temporal and spatial characteristics and dynamic evolution of China's animal husbandry carbon emissions[J]. Journal of Arid Land Resources and Environment, 2022, 36(06):65-71.
Xi Y L, Ye X M, Du J, et al. Research progress on carbon emission accounting methods in livestock and poultry breeding industry[J]. Jiangsu Agricultural Sciences, 2022, 50(04): 1-8.
Xu P, Houlton B Z, Zheng Y, et al. Policy-enabled stabilization of nitrous oxide emissions from livestock production in China over 1978-2017[J]. Nature Food, 2022, 3(5): 356-366.
Yao C S, Qian S S, Li Z T, et al. Provincial animal husbandry carbon emissions in China and temporal-spatial evolution mechanism[J]. Resources Science, 2017a, 39(4): 698-712.
Yao C S, Qian S S, Mao Y H, et al. Decomposition of impacting factors of animal husbandry carbon emissions change and its spatial differences in China[J]. Transactions of the Chinese Society of Agricultural Engineering, 2017b, 33(12): 10-19.
Yetişgin S O, Morgan-Davies C, Önder H. Comparison of farm-level greenhouse gas emissions in transhumance and semi-intensive sheep production systems in continental rangelands[J]. Animal, 2022, 16(8): 100602.
Yu G H, Beauchemin K A, Dong R L. A review of 3-nitrooxypropanol for enteric methane mitigation from ruminant livestock[J]. Animals, 2021, 11(12): 3540.
Zhang D L, Zhang P Y, Shen Y J, et al. Progress in the mechanism for the promotion of nitrogen loss reduction during the acidification storage of animal slurry[J]. Transactions of the Chinese Society of Agricultural Engineering, 2023, 39(8): 12-19.
Zhang H L, Chang Y, Lou W Q, et al. A review on novel traits in dairy cattle breeding[J]. Acta Veterinaria et Zootechnica Sinica, 2021, 52(10): 2687-2697.
Zhang J X, Wang H L. Regional differences, dynamic evolution and convergence analysis of carbon emissions from animal husbandry in China: Based on the animal husbandry data of 31 provinces (municipalities) in China from 1997 to 2017[J]. Jianghan Tribune, 2020, (09): 41-48.
Zhang R. Research on development strategy of green ecological circular livestock industry under the 'double carbon' goal[J/OL]. Feed Research, 2025, 48(01):237-240.
Zhang X, Sun S H, Yao S B. Influencing factors and spatiotemporal heterogeneity of livestock greenhouse gas emission: Evidence from the Yellow River Basin of China[J].Journal of Environmental Management, 2024, 358: 120788.
Zhang X X, Liu C J, Liao W H, et al. Separation efficiency of different solid-liquid separation technologies for slurry and gas emissions of liquid and solid fractions: A meta-analysis[J]. Journal of Environmental Management, 2022, 310: 114777.

Chapter 4

Low-carbon Energy Transition of China's Agrifood Systems

Fang Xia[1,2], Shu Yang[1,2], Xiaoshi Zhou[1,2], Yumei Zhang[1,2], Li Chai[1,2], Yuhan Zhao[1,2], and Ji Gao[3]

1. Academy of Global Food Economics and Policy, China Agricultural University
2. School of Economics and Management, China Agricultural University
3. Environmental Defense Fund (EDF) Beijing Representative Office

Key Findings

● Total energy consumption in China's agrifood system showed an overall upward trend between 2002 and 2022. However, its share in national energy consumption declined and stabilized. Coal remains the dominant energy source, although electricity's share exceeds 20%, signaling incremental progress in transitioning the energy mix.

● GHG emissions from energy consumption in China's agrifood system stabilized since 2015, remaining at approximately 630 million tonnes of CO_2eq. However, emissions rebounded between 2021 and 2022, reaching 673 million tonnes in 2022.

● The CAU-AFS model is used to project future GHG emissions from energy consumption in the agrifood system, utilizing two key parameters: energy intensity per unit output value and non-fossil energy share. Results show that by 2060, both the medium and high scenarios can effectively curb the emissions growth. Emissions under these scenarios are projected to reach 590 million tonnes and 396 million tonnes, respectively. This represents a decrease of 31% and 53% compared with the emissions under the baseline scenario.

● Energy transition pathways for the agrifood system vary across different stages. At the production stage, electrifying agricultural machinery can reduce energy intensity. Meanwhile, developing renewable energy sources and building smart microgrids can create a "new energy + industry" model. For pre- and post-production stages, improving energy efficiency and increasing the share of renewable energy is key, and preparing to account for carbon emissions will support the deeper advancement through a future market-based mechanism. Additionally, post-production waste can be converted into energy or processed into organic fertilizers.

Policy Recommendations

● First, energy transition in the agrifood system is a multidimensional, cross-sectoral and complex process extending beyond agriculture itself. As a result, establishing a foundational framework for cross-sectoral synergistic governance is essential to actively drive policy integration and innovate integration mechanisms.

● Second, advancing technologies through R&D and promotion is key. Nationally, priority lies in addressing

common technical challenges through basic research. Regionally, localities take the lead in developing adaptable, low-cost technological solutions tailored to local resource conditions, ecosystems, and agricultural characteristics to ensure sustainable implementation. At the application level, a differentiated promotional strategy must be deployed across distinct stakeholder groups.

- Third, information gaps constrain the agrifood system's energy transition. Constructing a dedicated information platform for agricultural energy transition can address this challenge. Such a platform would consolidate multiple functional modules to provide comprehensive, accurate and timely information support for all stakeholders.
- Fourth, expanding the use of existing market instruments, such as China Certified Voluntary Emission Reductions, in agricultural projects can incentivize the energy transition. Furthermore, exploring diverse incentive mechanisms is important to effectively motivate stakeholders across the agrifood system to pursue emission reductions through this transition.
- Fifth, collaborating on research and development with technologically advanced countries and sharing mature technological solutions with developing nations can accelerate technological innovation and upgrades. Proactively aligning with international regulatory frameworks and participating in their formulation and revision also support stakeholders in the agrifood system in addressing the challenges posed by the global energy transition.

4.1 Introduction

Agrifood systems and energy systems are inextricably linked and play a crucial role in advancing the Sustainable Development Goals (SDGs)[1] and fulfilling commitments under the Paris Climate Change Agreement (IRENA and FAO, 2021). In China, agrifood system energy transition carries triple significance.

1. GHG Mitigation

The agrifood system accounts for up to 14% of China's total GHG emissions (FAO, 2021), with energy use being a primary source. Promoting this energy transition is a key for reducing GHG emissions and achieving China's carbon peaking and carbon neutrality goals.

2. Agricultural Modernization

The evolution of agricultural modernization toward facility agriculture, smart agriculture and precision agriculture necessitates deep integration of energy-technology-production. This requires systemic shifts in energy supply:

● From centralized to decentralized architecture,
● From single-source to multi-energy complementary system, and
● From passive transmission and distribution to intelligent grid management.

Modernizing rural energy infrastructure is essential to overcome traditional constraints and unlock agricultural productivity.

3. Rural Socioeconomic Development

Rural households are dual stakeholders—as agricultural producers and participants in the modern energy transition. This shift generates new income streams through green energy production chains while bolstering renewable energy development in rural areas. These advances provide robust energy support for expanding agricultural value chains, enhancing product value-addition, diversifying operations, and ultimately raising farmer incomes. Critically, this transition reinforces poverty alleviation achievements and accelerates rural revitalization.

[1] The three most relevant SDGs are to end hunger and achieve food security (SDG 2), ensure access to affordable, reliable, sustainable and modern energy for all (SDG 7), and take urgent action to combat climate change and its impacts (SDG 13).

4.2 Energy Consumption and Greenhouse Gas Emissions in the Agrifood System

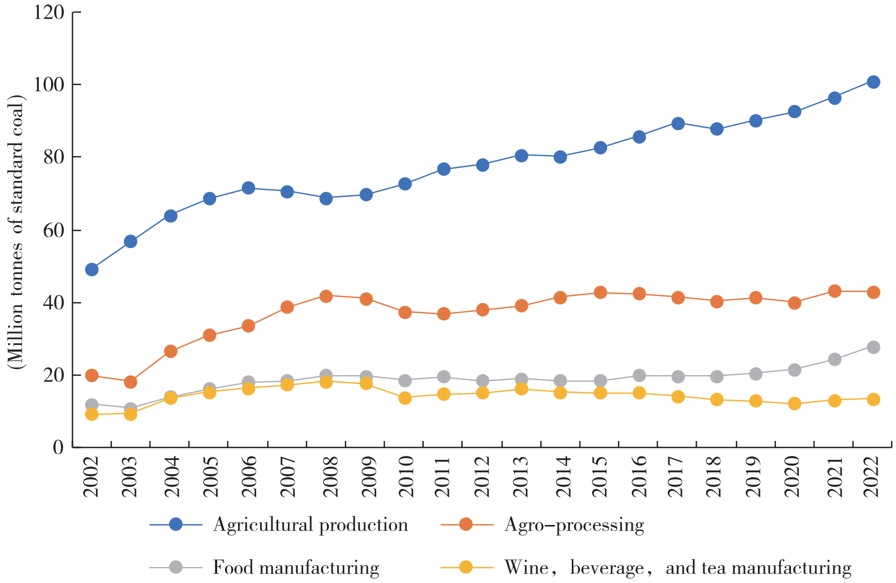
Prior to analyzing energy transition pathways, we clarify terminology using China's Energy Law, Renewable Energy Law, and methodologies from the International Energy Agency (IEA), the International Renewable Energy Agency (IRENA), and the Intergovernmental Panel on Climate Change (IPCC). We categorize energy by lifecycle carbon intensity: Clean energy refers to energy with low or negligible carbon emissions (solar, wind, hydro, biomass, geothermal, ocean, nuclear, and natural gas meeting ultra-low emission standards). Non-clean energy refers to energy with high carbon emissions or significant negative ecological impacts (mainly coal and oil).

Internationally, agrifood systems encompasses agricultural production, processing, transportation and storage, wholesale and retail, as well as waste management. China's sectoral data reveals distinct energy consumption trends (Figure 4-1). For example, energy consumption in the wine, beverage and tea manufacturing sector has remained relatively stable from 2002 to 2022. In contrast, the energy consumption of agricultural production, agrifood processing, and food manufacturing shows a significant upward trend (see Figure 4-1).[2]

Notably, despite the increasing energy consumption within the above sectors, their share in national energy consumption has declined or stabilized since 2011 (see Figure 4-2). This indicates that although the energy demand of the agrifood system expands, the growth rate of its energy consumption has not exceeded China's overall energy demand trajectory, maintaining a stable proportion of national energy use.

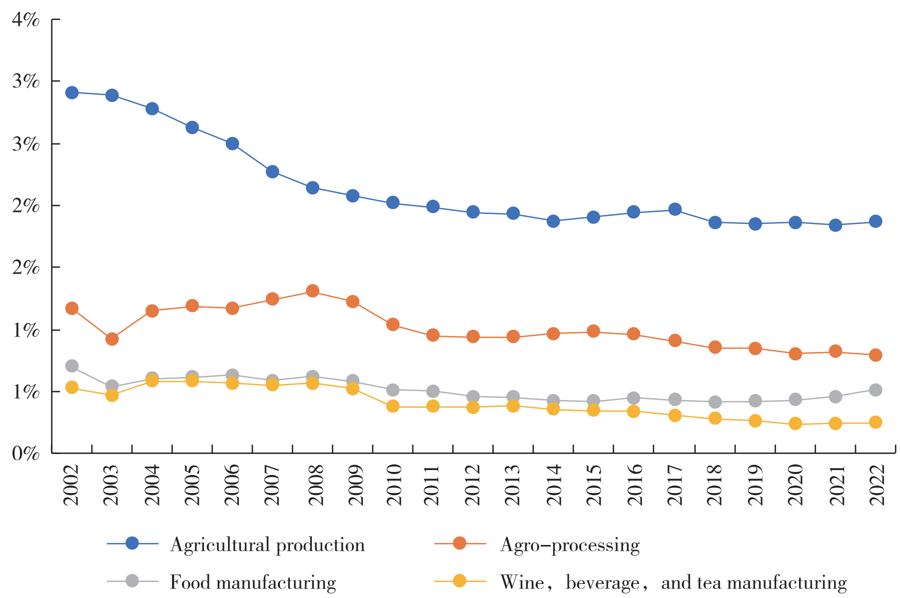
[2] This chapter selects data from 2002-2022. The year of 2002 saw the official issuance of the Electricity Reform Document No. 5 (full name: Notice on the Issuance of the Electricity System Reform Program), marking the beginning of China's electricity system reform. Energy data from 2022 is the most recent data available from the China Statistical Yearbook.

Figure 4-1 Energy Consumption in Agrifood System



Data source: China Statistical Yearbook 2004-2024

Figure 4-2 Share of Energy Consumption in Agrifood System



Data source: China Statistical Yearbook 2004-2024

Analyzing structural changes in energy consumption between 2002 and 2021 reveals a clear trend toward electrification. Although petroleum product use increased in agricultural production and natural gas consumption rose in post-production sectors (food manufacturing and food packaging), these sectors achieved significant coal substitution with electricity (see Figure 4-3).

Key structural shifts include (1) Coal's declining role: food manufacturing slashed coal dependency by 43%, followed by food packaging (23%), and agricultural production (11%). (2) Electricity's rising dominance: electricity share surged 16% in food manufacturing, 13% in food packaging, and 7% in agricultural production. By 2021, electricity constituted 33% of energy use in food manufacturing and 28% in food packaging, with even traditionally low-electrification agriculture reaching 24%. This ongoing transition highlights a sector-wide shift toward electricity as an increasingly important energy source

Figure 4-3 Share of Electricity in Energy Consumption in Agrifood System

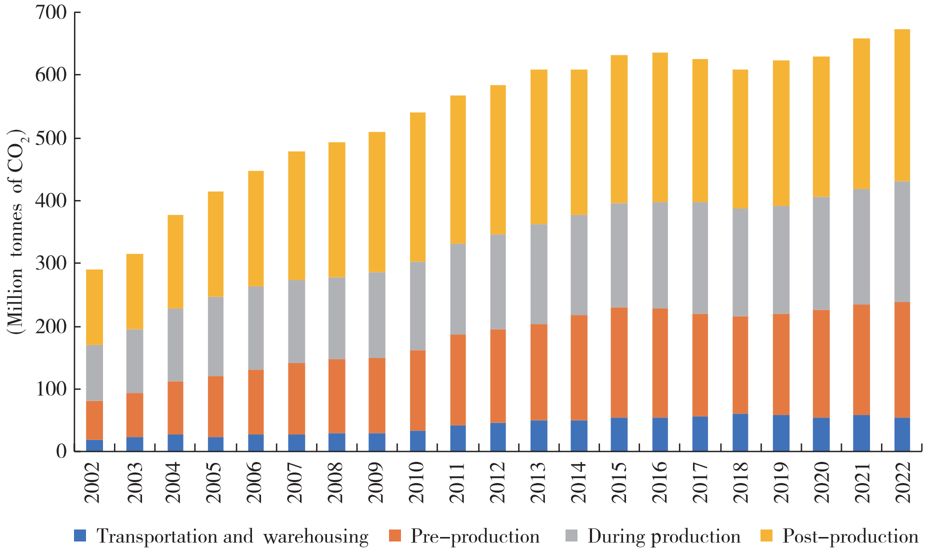
Data source: FAOSTAT 2002-2021

The progressive substitution of coal with electricity aligns strategically with China's broader power sector decarbonization, creating significant synergy for reducing agrifood system emissions. Modeling by China Agricultural University (CAU-AFS Model) indicates relative stabilization in energy-related GHG emissions from 2015 onward, maintaining at around 630 million tonnes (CO_2eq) annually. However, this plateau was disrupted as production intensified between 2021 and 2022, driving emissions to 673 million tonnes in 2022 (see Figure 4-4).

In analyzing the structure of emissions, we divide the agrifood system into the transportation and warehousing (treated as a separate category due to its cross-cutting nature) and three other stages: pre-production, production, and post-production. The pre-production stage includes the manufacturing of fertilizers, pesticides, plastics, and agricultural machinery, as well as wholesale, retail, and restaurant sectors. The production stage encompasses agriculture, forestry, animal husbandry, and fishery. Post-production involves agrifood processing, food manufacturing, alcoholic beverage and tea production, tobacco manufacturing, and wholesale, retail, and restaurant industries.

Between 2002 and 2022, the emission shares of transportation and warehousing and pre-production increased by 1.5% and 5.9%, respectively, while the shares from production and post-production decreased by 2.3% and 5.1%, respectively. In particular, since 2015, when total emissions have been relatively flat, the share from production rose by 2.5%, while the shares of emissions from post-production, pre-production, and transportation and warehousing fell by 1.4%, 0.7%, and 0.4%, respectively.

Figure 4-4 Greenhouse Gas Emissions from Energy Consumption in in Agrifood System



Data source: CAU-AFS model

4.3 Potential pathways for energy transition in the agrifood system

Energy transition in the agrifood system can be advanced through three main pathways:

1. The adoption of renewable energy;

2. The provision of raw materials for biomass energy production;

3. The supply of feedstocks for organic fertilizer production, replacing chemical fertilizers and thus reducing energy consumption in fertilizer manufacturing.

This section explores these transition pathways by examining the intrinsic linkages between the pre-production, production, and post-production stages of the agrifood system and the corresponding patterns of energy supply and demand.

First, given the differences between the use of electricity for agricultural production and commercial and industrial use in our electricity system, and the potential for agricultural outputs to be converted into biomass energy, this section will independently explore the energy transition in the production stage.

Second, following the FAO definitional framework, pre-production activities of the agrifood system cover the production of fertilizers and pesticides, while the post-production activities span food processing, transportation, packaging, retailing, and consumption, as well as the disposal of waste. It is important to distinguish waste disposal from other post-production activities, as it serves as a potential input for renewable energy production, rather than simply being a point of energy consumption. Therefore, after discussing the energy transition pathways for pre-and post-production stages, this section devotes an independent analysis to waste resource utilization, aiming to comprehensively illustrate the diversified pathways of energy transition in the agrifood system.

4.3.1 Energy Transition in Production

The replacement of fossil fuels with clean energy lies at the heart of China's agricultural modernization. Meanwhile, rising demand for new energy in rural areas highlights the strategic value of scaling up renewable energy adoption. Accelerating the deployment of renewable energy systems and technologies in rural areas can catalyze a transformative shift in agricultural production methods, reconfigure the foundations for low-carbon agricultural development, and systematically reshape the development capacity of farmers, farms, rural communities by upgrading the energy supply system.

The "Pilot Counties Construction Program for the Rural Energy Revolution," released in 2023, outlines a basic framework for the energy transition in the production stage. The program's core tasks include:

● Establishing a diversified renewable energy supply system,

● Promoting electricity substitution,

● Upgrading rural power grids, and
● Expanding direct end-use applications of renewable energy.

(1) Rural Renewable Energy Construction and Grid Upgrading

As a flagship initiative under the rural energy revolution, the "Thousand Towns and Ten Thousand Villages Wind Action" has made significant progress since its launch. At present, the action has been rolled out in Shanxi, Inner Mongolia, Anhui, Jiangxi, Hubei, Yunnan, Shaanxi, Gansu, Ningxia. Each province has tailored implementation strategies to local conditions. For example, Jiangxi prioritizes pilot areas with grid consumption capacity, while Shaanxi has established an exit mechanism to withdraw development rights from delayed projects.

In Yunnan, 31 initial wind power projects have been launched with a total installed capacity of 535,300 kilowatts. Beyond technical deployment, these projects generate economic benefits: the Guanzhuang Wind Farm in Ye County, Henan, attracted over ten village cooperatives to invest in shares, yielding over 3 million yuan in dividends within three years. Technological innovation also plays a role; for instance, Sinoma Technology has developed low-noise blade technology that effectively enhances power generation performance while minimizing environmental impacts in residential areas.

While the Wind Action reflects policy innovation, China's photovoltaic poverty alleviation program implemented since 2013 laid the groundwork for the "Thousand Families and Ten Thousand Households Solar Action". Anhui was the first to pilot rooftop solar installations on the homes of low-income households and on idle collective land, generating income through self-consumption and surplus grid sales. This model was scaled nationally in 2016, when and five ministries and commissions, including the NDRC, jointly issued the "Opinions on the Implementation of Photovoltaic Power Generation for Poverty Alleviation", targeting 35,000 impoverished villages in 471 counties in 16 provinces. The goal was to benefit 2 million labor-constrained households, raising annual income by 3,000 yuan per household.[3]

[3] Relevant information is available at https://www.nea.gov.cn/2016-04/05/c_135250679.htm.

According to the 2024 White Paper on China's Energy Transition released by the State Council Information Office, rural household photovoltaic capacity now totals 120 million kilowatts, benefiting over 5.5 million farming households. This has increased farmers' income by approximately 11 billion yuan each year and created around 2 million jobs. Compared with earlier efforts, the "Thousand Families and Ten Thousand Households Solar Action" introduces upgraded implementation models, including:
● A market-oriented approach balancing government oversight and enterprise participation.
● Sustainable benefit-sharing mechanisms.
● Integration of photovoltaic microgrids and energy storage technologies to address grid absorption and transformer constraints, facilitating a transition toward intelligent, decentralized rural energy systems.

In addition to wind and solar energy, biomass energy derived from agricultural outputs, such as corn, sugar cane, cassava and other crops, also plays a role in rural renewable energy pathways. However, concerns over food security (Ren et al., 2023) have prompted China to pivot from grain-based ethanol to non-grain biomass. The evolution is evident in policy shifts:
● The 2001 Ethanol Gasoline Pilot Program supported corn ethanol in nine provinces.
● By the 11th Five-Year Plan, grain-based ethanol projects were halted.
● The 2006 Biofuel Ethanol Development Plan prioritized non-grain sources.
● In 2020, the Guiding Opinions on Promoting Non-Grain Biomass Liquid Fuels cemented a focus on waste grain and non-grain crops (Wu et al., 2021).

To avoid competition with arable land, innovative approaches such as the development of marginal lands (Cao et al., 2021) have been explored.

Large-scale renewable energy deployment depends not only on resource development but also on robust grid support. Since the 1990s, China has gradually eliminated power supply blind zones through several rounds of agricultural grid construction projects. A major milestone was the 2013 Three-Year Action Plan to achieve full electricity access. By the end of 2015, China completely solved the problem of electricity access for 39,800,000 off-grid residents, especially in remote areas like Qinghai, gained power access, achieving universal rural electricity coverage.

In the current phase, grid transformation efforts since 2016 emphasize smart and low-carbon upgrades:

- Enhancing flexibility via transformer capacity increases and smart meter deployment,
- Developing digital O&M platforms for real-time prediction of distributed generation and dynamic load matching.

A notable example is the distributed smart microgrid in Laiwu, which features a household photovoltaic and energy storage pilot demonstration project (see Box 4-1).

Box 4.1 Distributed photovoltaic smart microgrids

Basic information

In June 2023, Jinan's first distributed smart microgrid—a pilot demonstration project combining household photovoltaics and energy storage—was completed and put into operation in Chenjiazhuang, Fangxia Town, Laiwu District.

The project leverages new technologies such as 5G and the Internet of Things to create a strong system integrating household photovoltaics with advanced energy storage technologies, enabling coordinated control of electricity loads and providing fully green electricity.

This proactive exploration serves as a model for rural self-sufficiency in electricity, aids in pollution reduction and carbon emissions, and supports energy transition, providing a "Laiwu Solution."

Main practices

Distributed smart microgrid adopts the typical solution of "distributed photovoltaic + decentralized energy storage + localized load." By optimizing and integrating resources from the power supply side, grid side, load side, and energy storage side, it forms a new energy-dominated smart microgrid demonstration model. The decentralized energy storage establishes low-voltage interconnection with nearby transformer zones, achieving regional power generation-load balance. Currently, the Chenjiazhuang photovoltaic and energy storage system, along with nearby charging piles and the Chenjiazhuang North transformer zone, forms a smart distributed microgrid. In the event of an outage in the superior power supply, the distributed smart microgrid centered on Chenjiazhuang can maintain uninterrupted power supply in islanded mode.

From a technical perspective, this smart microgrid integrates distributed power sources, energy storage devices, power conversion equipment, related loads, and monitoring and protection devices. Utilizing advanced technologies such as integrated photovoltaic-storage terminals, a "trusted WLAN" edge communication network, and a source-grid-load-storage control system, it creates an auton omous system capable of self-control, self-protection, and self-regulation. This small-scale power generation and distribution system can operate either connected to the external grid or independently.

The project adopts a "local generation, local consumption" model. By leasing rooftops throughout Chenjiazhuan, it promotes comprehensive photovoltaic construction across the village. The first phase has a capacity of 700.325 kW, with a long-term total capacity planned at 2 MW. Instead of the traditional household grid-connection approach, the project uses a "centralized convergence and voltage boosting" model, connecting to the local grid via a 10 kV line, thereby enhancing the integration of renewable energy into grid load control.

A 200 kW/400 kWh energy storage system has been installed to create a typical application scenario for distributed energy storage. During peak photovoltaic generation periods, coordinated interaction among "generation, storage, charging, and consumption" optimizes resource utilization, maximizes power generation benefits, and promotes clean energy use in rural areas. This serves as a model for advancing "county-wide photovoltaic + decentralized energy storage" development.

To enhance the grid's photovoltaic power absorption capacity, the project has independently developed an integrated photovoltaic-storage terminal, combining energy management, information communication, network security, active power control, and reactive power control. This enables deep integration of photovoltaic and energy storage resources, making them "observable, measurable, adjustable, and controllable."

Additionally, to address communication challenges in distributed photovoltaic systems, a "trusted WLAN"-based edge transmission network has been established to strengthen information transfer. Data is uploaded to the grid dispatch system via a 5G power private network, significantly improving communication and control reliability.

Upon completion and operation, the theoretical maximum photovoltaic generation capacity reaches 652.2 kW, exceeding the village's peak power demand. This enables the entire village to be supplied with 100% green electricity, with surplus power stored or fed into the grid.

Source: http://fgw.shandong.gov.cn/art/2022/7/29/art_91679_10360921.html.

(2) Electrification of Agricultural Machinery

Since the introduction of agricultural machinery emission standard in 2008 and the implementation of the National Stage IV Emission Standards in 2022, China has continued to strengthen emissions control in agricultural machinery sector. However, due to the long service life of agricultural equipment, environmental issues in the field remain prominent. According to a report by the Ministry of the Environment,[4] in 2022, particulate emissions from mechanized production in China's plantation and animal husbandry industries (91.8 Gg) are significantly higher than emissions from motor vehicle sources (53 Gg).

Electrification technologies offer a viable path to reduce emissions from agricultural machinery. A systematic review by Scolaro et al. (2021) shows that electric drive systems can achieve up to 30% energy efficiency improvement compared to traditional hydraulic drives, as demonstrated in agricultural equipment such as seeders and sprayers. In terms of emissions performance, field trial data show that small electric tractors in the 10kW class can achieve about 70% CO2 reductions (Ueka et al., 2013). In addition, electrification provides fundamental support for the implementation of precision agriculture technologies, which indirectly reduce environmental burdens through, for example, the precise application of chemicals on demand.

To promote the green transformation of agricultural machinery, a series of national policy documents, such as the "Strategic Plan for Rural Revitalization (2018-2022)," the "Guiding Opinions on Accelerating Comprehensive Green Transformation of Agricultural Development to Promote Rural Ecological Revitalization," and the "Comprehensive Rural Revitalization Plan (2024-2027)," explicitly call for the promotion of energy-saving and environmentally friendly agricultural machinery and equipment. In line with these goals, both national and local governments have introduced financial subsidies and financial support measures, such as the inclusion of electric agricultural machinery in the scope of agricultural machinery purchase subsidies.

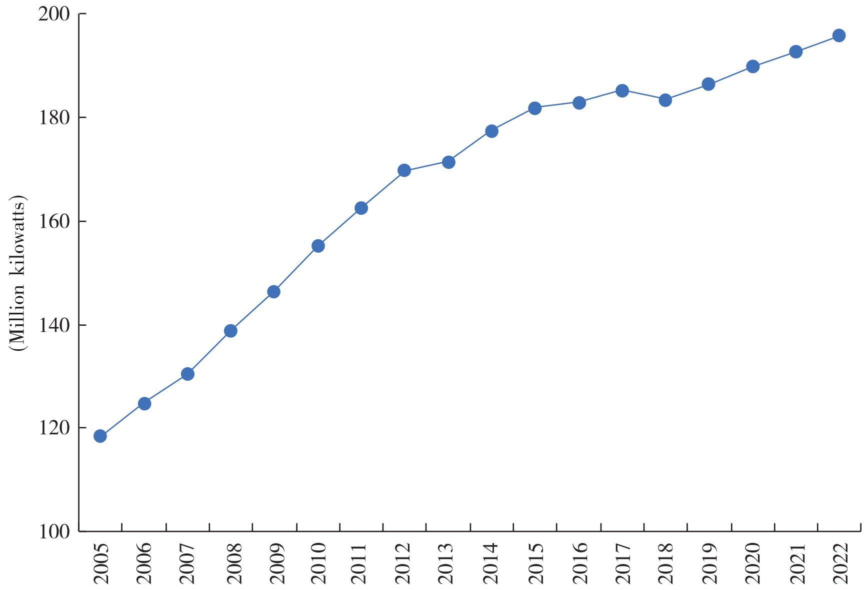
Two key indicators reflect the level of agricultural electrification and digital transformation:

- Electric motor power of agricultural machinery indicates the scale of electricity use in agricultural production.
- Agricultural aircraft (especially drones) reflect the integration of digital and intelligent technologies in agricultural practices. These aircraft, typically powered by electricity, are used in plant protection, seeding, fertilization, and monitoring. They are instrumental in advancing precision and smart agriculture, representing the forefront of agricultural digital transformation.

In terms of the national trends, agricultural electric motor power in China has continued to grow significantly between 2005 and 2022 (see Figure 4-5). The total installed electric motor power increased from 118.49 million kilowatts (kW) in 2005 to 195.84 million kW in 2022, representing a growth rate of about 65% over seventeen years. Notably, the growth rate has accelerated significantly in recent years, especially since 2019, when electric motor power grew by nearly 10 million kW in just four years, reflecting a marked increase in the average annual growth rate.

[4] Ministry of Ecology and Environment of the People's Republic of China, "China Mobile Source Environmental Management Annual Report (2023)," https://www.mee.gov.cn/hjzl/sthjzk/ydyhjgl/202312/t20231207_1058460.shtml.

Figure 4-5 Development Trend of Agricultural Electric Motor Power in China



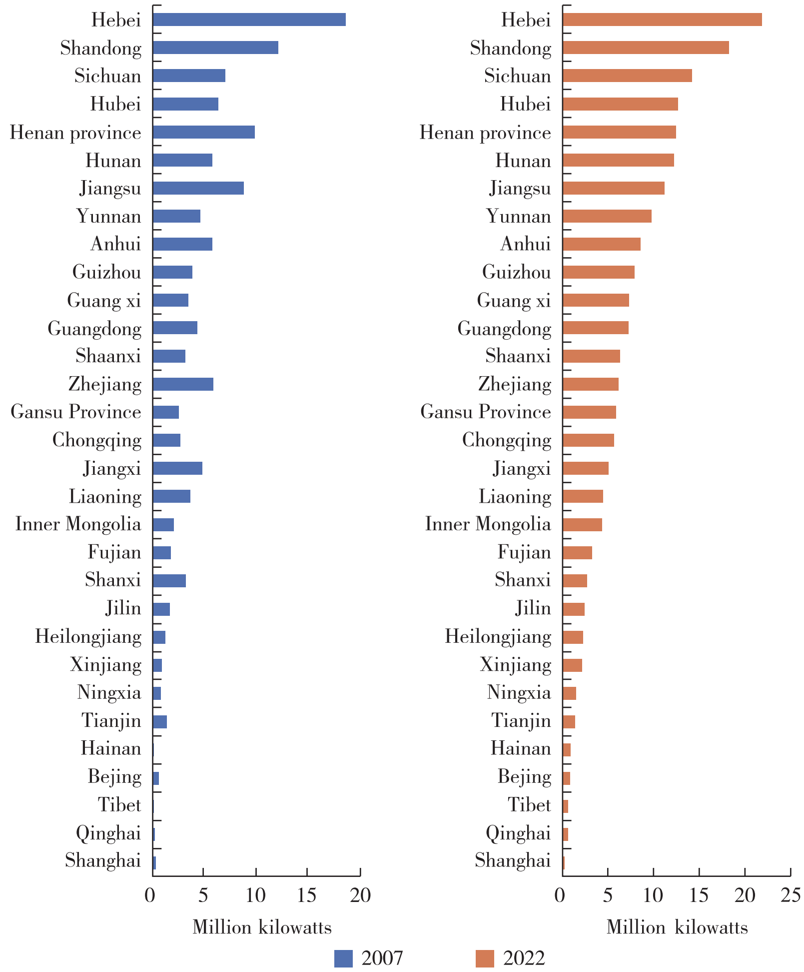
Data source: China Agricultural Machinery Industry Yearbook 2006-2023

At the provincial level, there are significant differences in the development level of agricultural motorization in various regions, which reflects the regional economic imbalance and the diversification of agricultural industrial structure (see Figure 4-6). Eastern coastal regions such as Jiangsu, Shandong, Hebei and Zhejiang have consistently ranked among the top in terms of electric motor power. This is supported by robust economies, a strong industrial base, well-developed rural power grids, and a high level of agricultural modernization. For example, Jiangsu recorded 1,099 kW of agricultural motor power in 2022, leading the country in agricultural electrification.

Central agricultural provinces, such as Henan, Hubei, Hunan, and Anhui, have experienced rapid growth in electric motor power, gradually narrowing the gap with the eastern regions. As major grain-producing areas, they have seen increasing demand for electric agricultural machinery and have benefited from national strategies like the "Central Rise" and the rural revitalization strategy. These initiatives have driven continuous improvements in agricultural infrastructure and accelerated electrification

In western regions such as Tibet, Qinghai, Ningxia, electric machine power remains relatively low, and development has been slower. However, provinces such as Sichuan, Yunnan, and Shaanxi have achieved relatively high levels of agricultural motorization, with rapid growth rates, indicating that electrification is also advancing steadily in parts of the west. Additionally, some provinces such as Inner Mongolia and Xinjiang, while currently having smaller installed capacities, have demonstrated strong growth momentum and significant development potential, suggesting that agricultural electrification holds considerable promise in these regions.

Figure 4-6 Development Trend of Agricultural Electric Motor Power in China by province



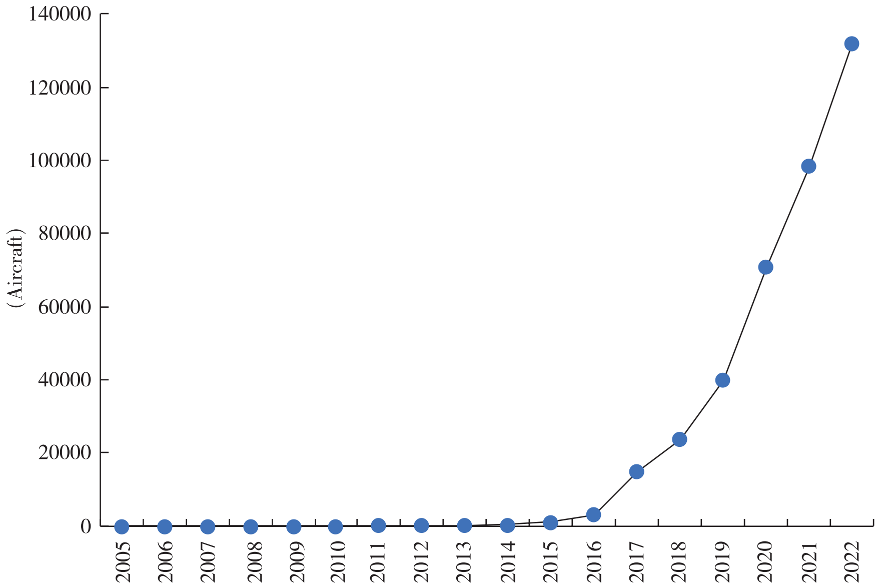
Data source: China Agricultural Machinery Industry Yearbook 2008 and 2023

The national development trend of agricultural aircraft is similar to the growth of electric motor power, both showing strong growth momentum, especially in recent years. From 2005 to 2015, the number of agricultural aircraft nationwide grew at a relatively slow pace and even stagnated during certain years (see Figure 4-7). This slow growth reflected the early-stage challenges in applying digital technologies to agriculture, including high technological costs, limited application scenarios, and low market acceptance.

However, since 2016, and especially after 2019, the sector has experienced a period of rapid expansion. The number of agricultural aircraft tripled within just three years, rising from 39,945 units in 2019 to 132,119 units in 2022. The explosive growth can be attributed to several key factors: the rapid maturation and cost reduction of drone technologies, increasing recognition of their effectiveness in agricultural applications, and strong support of national policies. Drone use in the agriculture has become increasingly widespread, covering functions such as crop protection, seeding, fertilization, and field monitoring. At the same time, a series of national policies promoting smart and precision agriculture has created a favorable environment for the adoption of agricultural aircraft.

The rapid expansion of agricultural aircraft use is not only a surge in quantity, but also a fundamental shift in production methods. It marks a critical milestone in the digital and intelligent transformation of Chinese agriculture, where traditional manual and labor-intensive practices are increasingly being replaced by a more efficient, precise and green modern agricultural production mode of modern agricultural production.

Figure 4-7 Development Trend of Agricultural Aircraft in China



Data source: China Agricultural Machinery Industry Yearbook 2004-2023

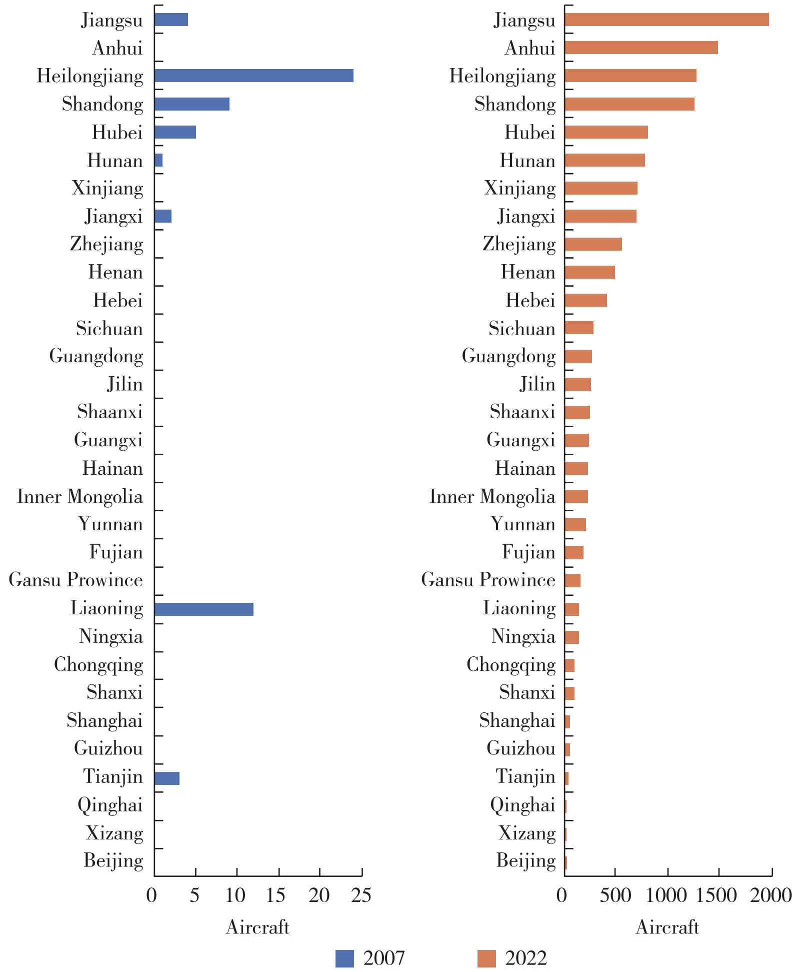
Provincial data reveals significant differences in the adoption of agricultural aircraft across regions (see Figure 4-8), with distinct distribution patterns compared to electric motor power. This reflects the localized and application-specific nature of digital technology in agriculture. Jiangsu, Anhui, and Heilongjiang are in the leading position nationwide in the deployment of agricultural aircraft. As major agricultural provinces, Jiangsu and Anhui feature extensive land consolidation and a pressing demand for efficient, precise agricultural technologies. In these regions, agricultural aircraft are widely used, especially for plant protection and precision fertilizer application, which significantly improve the efficiency and quality of agricultural production.

Heilongjiang, an important grain producing area with vast arable land, has also seen large-scale adoption of agricultural aircraft due to their unique advantages in plant protection and seeding. In addition, economically advanced provinces like Shandong and Zhejiang have also performed well in agricultural aircraft application. These regions benefit from strong economic foundations, high receptivity to new technologies and models, and robust development of digital agriculture. As a result, the prevalence and sophistication of agricultural aircraft usage in these regions are relatively high.

It is worth noting that some western provinces such as Xinjiang, Inner Mongolia and Shaanxi have also shown rapid growth in agricultural aircraft adoption. With vast territories and challenging terrain, Xinjiang and Inner Mongolia face obstacles with traditional farming methods. Agricultural aircraft not only improves production efficiency and reduces labor intensity, but also advances agriculture modernization in these areas. In Shaanxi and similar regions, the push to develop specialty and modern agriculture has generated growing demand for digital technologies, fostering a strong momentum for agricultural aircraft development.

The provincial distribution of agricultural aircraft reflects the growing penetration of digital technology in Chinese agriculture and the continuous expansion of its application scenarios. What began in a few developed regions has now spread nationwide, and what started with plant protection has extended to multiple functions such as seeding, fertilization and monitoring. Digital technology is thus reshaping agricultural production models in China, driving the sector toward greater efficiency, precision, and sustainability.

Figure 4-8 Development Trend of Agricultural Aircraft in China by province



Data source: China Agricultural Machinery Industry Yearbook 2008 and 2023

Despite the huge potential of agricultural machinery electrification, its widespread adoption still faces multiple challenges. From a technological perspective, the mismatch between power demand and battery energy density is particularly prominent. Taking a 157kW large tractor as an example, it requires a battery capacity of as high as 662.2kWh (Brenna et al., 2018), while the current energy density of lithium-ion batteries is only about 1/50 of that of diesel fuel (Scolaro et al., 2021). On the market side, user research has shown that farmers prioritize equipment reliability over environmental benefits (Flint et al., 2014). Cost-benefit analyses further reveal that although electric agricultural machinery can reduce operating costs by about 60%, the incremental payback period for models above 22.6kW still takes 2.05 years (Gao and Xue, 2020). In addition, the lack of charging infrastructure in rural and field environments also restricts the large-scale application of battery-powered solutions.

(3) New energy + industry model

Microgrids and source-grid-load-storage integration are important forms of distributed renewable energy projects that enable efficient utilization and self-sufficiency of energy by integrating local renewable resources. A microgrid is a small, decentralized power system that can operate independently from, or in connection with, the main power grid. In rural areas, microgrids can harness solar, wind, and other local renewable energy sources to provide green electricity to nearby farmers and agribusinesses. This decentralized power supply not only improves the efficiency but also enhances the stability and reliability of the power system.

Source-grid-load-storage integration refers to the coordinated linkage between power sources, electricity grids, loads, and storage systems, forming a highly integrated and responsive energy system. In rural renewable energy projects, this integration enables efficient utilization and storage of renewable energy, as well as flexible load management. By balancing energy supply and demand, it enhances both the economic viability and sustainability of rural energy systems.

These technologies facilitate the development of distributed renewable energy projects and promote the direct supply of green electricity. Meanwhile, the electrification of agricultural production, particularly in planting and livestock farming, drives strong demand for clean energy. In the crop production sector, electrification includes the modernization of irrigation systems and the intelligent control of greenhouse environments. Electric irrigation pumps allow for precise water management, while the electrification of greenhouses involves upgrading lighting, ventilation, and temperature control systems. The adoption of LED lighting, smart ventilation, and temperature control devices allows for accurate regulation of environmental factors such as light, temperature, and humidity, providing optimal growing conditions for crops.

In the livestock sector, electrification encompasses the automated and intelligent monitoring of feed processing and environmental management. By the use of electric feed processors and smart monitoring systems, critical processes can be managed with greater precision, enhancing farming efficiency and animal welfare.

China's strong policy support for the new energy industry, especially through innovative initiatives such as the photovoltaic poverty alleviation program, has greatly contributed to the rapid growth of distributed renewable energy capacity in rural areas. Along with the improvement of supporting facilities and the electrification of agricultural machinery, these efforts have paved the new paths for greater local consumption of renewable energy and have diversified rural economies. Across the country, there has been active experimentation and practice in integrating renewable energy with agricultural development, leading to a wealth of practical experiences (see Box 4-2).These experiences cover the localized application of renewable energy technologies and the deep integration of new energy and the agricultural value chain, providing valuable references for the nationwide promotion of the of "new energy + industry" development model.

In 2021, the NEA, the Ministry of Agriculture and Rural Affairs, and the National Rural Revitalization Administration jointly issued the "Implementation Opinions on Accelerating Rural Energy Transformation Development to Support Rural Revitalization." This document clearly sets the goal of "actively cultivating the new energy + industry" model, marking a new phase in the integrated development of renewable energy and agriculture in China.

Box 4.2 Agricultural Solar Complementary Emerging Industries

Basic information

Since the construction of the first batch of pilot projects in 2017, Weiyuan County in Dingxi City, Gansu Province, has implemented village-level photovoltaic poverty alleviation projects totaling 60.249 megawatts. This initiative has built 208 power stations with capacities ranging from 300 kW to 500 kW across 135 villages. It has established a positive operational system where village-level power stations enhance collective economic income, farmers receive wages through public welfare positions related to electricity generation, and village committees use the revenue to support vulnerable households.

By developing complementary agricultural industries such as "photovoltaics + edible fungi," "photovoltaics + vegetables," "photovoltaics + traditional Chinese medicine seedlings," and "photovoltaics + livestock farming," the project aims to achieve land intensification and maximize benefits. This approach fosters a comprehensive industrial development model that integrates solar power on rooftops, agriculture on the ground, local employment opportunities, and logistics and storage support in key towns.

Main practices

The innovation park in Weiyuan County follows a centralized joint construction model at the village level and a cross-regional joint construction model at the township-village level. By adopting a modern agricultural development approach, it aims to strengthen the agri-photovoltaic industry through green agricultural practices.

Meanwhile, the state-owned investment company, Weiyuan Zhengyuan Poverty Alleviation Development Co., Ltd., has introduced preferential policies such as "zero rent" and "three years rent-free followed by two years at half rent" to attract private enterprises that withdrew from the first phase of photovoltaics projects. These policies encourage them to reinvest and re-engage in the county's

"Photovoltaics + Edible Mushroom" Poverty Alleviation Industrial Park. As a result, it has fostered a comprehensive framework for social poverty alleviation and industrial development.

Following the principles of "professional operation and maintenance (O&M) enterprises, guaranteed annual power generation, and reasonable O&M costs," the county selects qualified O&M companies through open tendering to ensure stable and sustained power generation. A minimum annual generation of 1,300 kWh per kW is required; failing this, 30%-70% of the O&M fees will be deducted to maintain consistent output. To effectively reduce O&M costs, a 10-year fixed contract was established, with O&M fees set at 0.08 yuan per watt and key equipment warranties extended by three years, strengthening compliance oversight and preventing cost escalations or disputes over equipment replacement responsibilities.

Additionally, daily supervision is reinforced by assigning village-appointed custodians (selected from registered low-income households) to each power station. O&M companies provide professional training and performance-based assessments, with wages paid according to evaluation results. This resolves challenges in managing dispersed village-level stations and ensures the long-term sustainability of the photovoltaic industry.

By implementing a "four-in-one" industrial development model (leading enterprises + cooperatives + base/park + farmers) and an income-boosting mechanism of "five unifications, one decentralization, one standard, and three improvements" (unified land planning, training, supply of seeds/inputs, technical management, and market linkage; decentralized household production and benefits; standardized industrial bases; and enhanced organization of industries, farmers, and market entities), the county has effectively addressed issues such as low industrial organization, weak resilience to market/natural risks, and inefficiencies in individual operations. The "earned income retention" mechanism also prevents "policy-induced dependency."

This model extends beyond agri-photovoltaics. Industries like flower cultivation in Shangwan Town and Lianfeng Town similarly thrive, with 38 leading enterprises and 1,340 cooperatives driving income growth for 32,480 households, laying a solid foundation for rural revitalization.

Achievements

By 2021, Weiyuan County had established:

4 PV-edible mushroom industrial parks (Huichuan, Tianjiahe, Luyuan, Lianfeng)

12 large-scale "photovoltaics + mushroom" bases (e.g., Yuangudui, Zhanpo, Sanhe)

7 "photovoltaics + vegetable" bases

2 "photovoltaics + medicinal herb seedling" bases

1 "photovoltaics + livestock" base

1 "photovoltaics + industrial workshop" base

33 distributed "photovoltaics + industry" sites across all townships

The photovoltaics industry not only achieves spatial complementarity between agriculture and solar power but also ensures year-round productivity. The county has developed:

1,600 mu of agri-photovoltaics mushroom farms

750 mu of facility-grown vegetables, codonopsis, and astragalus seedlings

150 mu of specialty livestock farming

An 85%+ complementary utilization rate

Annual production of premium mushroom reaches 4,511.35 tonnes, generating over 79.3385 million yuan in revenue. The triple economic benefits—land lease fees, contracted operation income, and employment wages—are becoming increasingly evident.

These projects have attracted 8 leading enterprises and 16 standardized cooperatives, resulting in an annual income boost of over 23,600 yuan per household for 1,478 households. Photovoltaic power generation profits additionally benefit 12,000 households, increasing incomes by 2,000-6,000 yuan annually. With expanded revenue streams for villages and farmers, the synergistic effect of agri-photovoltaics integration continues to grow, completing the transition from a poverty-alleviation industry to a vital revitalization industry.

Source: http://www.moa.gov.cn/xw/qg/202111/t20211130_6383270.htm

4.3.2 Energy Transition in Pre-and Post-Production

Currently, there are no mandatory emissions limits for the pre-and post-production sectors of the agrifood system. However, as the carbon emissions trading system gradually expands, these sectors are likely to face increasingly stringent emission regulations. In addition, listed and quasi-listed companies are required to fulfill the obligation of disclosing environmental, social and corporate governance (ESG) information,[5] subjecting their green operations to broader public scrutiny. In light of this, enterprises in the pre-and post-production stages of the agrifood system should proactively align with emerging standards and strategically plan for energy transition to ensure an orderly and sustainable shift.

(1) Accounting for Carbon Emissions

In conducting carbon emissions accounting, enterprises can adopt methods best suited to their own situations and actively engage with potential carbon emissions trading mechanisms. Internationally, the Greenhouse Gas Protocol (GHG Protocol), a widely recognized standard, provides important guidance for enterprises and governments in GHG management accounting and reporting (Morawicki and Hager, 2014). In addition, the ISO 14064 standard provides detailed specifications for quantifying and reporting GHG emissions and removals, enhancing the scientific rigor and accuracy of carbon accounting (Henderson-Sellers and McGuffie, 2012). Between 2013 and 2015, China's climate change authorities issued three batches of GHG accounting and reporting guidelines covering 24 industries. Among them, the "Guidelines on GHG Emission Accounting Methodology and Reporting for Food, Tobacco and Alcohol, Beverages and Refined Tea Enterprises" specifically targets sectors within the agrifood system. In addition, guidelines for the power, iron and steel, cement, and electrolytic aluminum industries are currently being updated align with the evolving requirements of the carbon market (Bian et al., 2024). Although these sectors are not directly related to the agrifood system, their methodologies offer valuable references for related enterprises and help inform future developments in carbon accounting practices.

(2) Improving energy utilization efficiency

Since 2019, China has actively promoted an action plan for industrial energy efficiency diagnostic services. The core objective of this plan is to provide professional energy-saving diagnostics to enterprises with relatively weak energy management foundations, particularly in key high-energy-consuming industries.[6] This plan focuses on five core areas: conducting in-depth analyses of energy loss control and the effective utilization of waste heat and residual energy to explore energy-saving opportunities; assessing the potential energy-saving effects of upgrading energy-consuming equipment or optimizing operational controls; reviewing and enhancing the energy management system to achieve higher energy efficiency; focusing on the optimization of process workflows and improvements in production organization to tap into energy-saving potential; and analyzing the adjustment of energy structures and the overall optimization of energy systems to seek further avenues for energy savings. Notably, the scope of this action plan includes pre-production fertilizer enterprises and post-production food enterprises in the agrifood system. For participating enterprises, these diagnostic services offer customized energy-saving solutions and support more efficient energy use. In addition, from a broader perspective, identifying common challenges across the industry and transforming them into publicly available insights can offer valuable references for other enterprises, thereby contributing to overall improvements in energy utilization efficiency.

(3) Using renewable energy power

Currently, Chinese enterprises can obtain renewable energy power through three primary avenues: First, companies can invest in building their own renewable energy facilities to achieve self-sufficiency in green power supply. Second, they may participate in in "bundled" green power trading, where renewable energy certificates (RECs) and electricity are sold together, enabling direct procurement of green electricity. Third, through "unbundled" green certificate trading, where RECs are traded separately from electricity, companies can acquire the environmental attributes associated with green power.

The primary challenge for enterprises investing

[5] In April 2024, the Shanghai and Shenzhen Stock Exchanges officially released the Guidelines on Sustainability Reporting for Listed Companies under the guidance of the China Securities Regulatory Commission (CSRC), marking a new stage of ESG disclosure for listed companies in China. Based on the framework of the Guidelines, the CSI North Exchange further issued the "Self-Regulatory Guidelines for Listed Companies-Preparation of Sustainability Reports (Draft for Public Comments)" in November, clarifying that the subjects of mandatory disclosure include, among others, sample companies that have been continuously included in the SSE180 Index, the KIC 50 Index, the SZSE 100 Index and the GEM Index, as well as domestic and foreign listed companies that have issued A or B shares in China, and at the same time have issued H or D shares and other foreign share capital as well as depositary receipts (GDRs) outside China.

[6] Information on related services is available at https://www.chinanecc.cn/website/News!view.shtml?id=288149.

in self-provided green power facilities comes from the uncertainty of renewable energy policies. Renewable energy sources, such as wind and solar are inherently variable and intermittent, unlike traditional energy sources that can provide a steady power supply. To ensure a stable energy supply from these variable sources, companies with "self-generation and self-consumption" model need supporting infrastructure, such as energy storage systems, which significantly increase upfront investment costs. Alternatively, enterprises opting for a "residual power on-grid" mode, where surplus electricity is fed into the grid, must navigate cost-sharing mechanisms related to the use of grid services. These factors critically influence both investment decision and investment scale.

Although China's electricity market is gradually improving (Li et al., 2024), frequent policy adjustments still introduce significant uncertainty into long-term investment planning. This is especially relevant for enterprises in the agrifood system, which are currently not subject to mandatory emission reduction obligations. As a result, policy uncertainty may further dampen their willingness to invest in green power. Enterprises must therefore carefully consider potential risks when exploring renewable energy adoption, balancing economic benefits with their broader environmental and social responsibilities.

Enterprises can also accelerate their energy transition by actively participating in green power and green certificate trading. According to the "Basic Rules for Medium-and Long-Term Electricity Transactions-Special Chapter on Green Electricity Transactions", jointly issued by the NDRC and the NEA in 2024, China's green electricity transactions, as a key component of medium- and long-term electricity transactions, are governed by standardized market rules. Power trading institutions are responsible for organizing green power transactions across different time cycles, such as annual (or multi-year), monthly (or multi-month), and intra-month (e.g., ten days, weekly, and daily rolling) periods. These transactions may occur at both intra-provincial and inter-provincial levels, using bilateral negotiations, listed transactions, and other formats to meet varying enterprise needs.

In terms of green certificate trading, the "Renewable Energy Green Power Certificate Issuance and Trading Rules" issued by the NEA in 2024 stipulate that RECs may be traded either individually or in combination with electricity. Trading contracts allow both parties to agree on key terms such as quantity, price, and delivery time, thereby ensuring transaction transparency and stability. Green certificate trading is organized through multiple channels, including listed trading, bilateral negotiation and centralized bidding, and is governed by market-based price formation mechanisms, reflecting a high degree of marketization. These trading mechanisms cover a wide range of renewable energy generation types, including but not limited to wind power (onshore and offshore), solar power (photovoltaic and solar thermal), conventional hydropower, biomass, geothermal, and ocean energy.

This diversity of market mechanisms provides enterprises with flexible and tailored options, boosting market vitality and accelerating the green transition of China's energy structure. However, despite these opportunities, several challenges remain. For instance, China's current electricity pricing mechanism has not yet fully achieved marketization. As a result, it is difficult for power generators and consumers to align on long-term price forecasts, increasing the uncertainty about future electricity costs. This uncertainty often compels market participants to favor short-term trading strategies to mitigate potential market risks. Compounding this issue is the absence of a functioning electricity derivatives market, leaving market players without effective tools to hedge against price volatility or generation/consumption mismatches. Consequently, although the volume of green power transactions in China has expanded significantly in recent years,[7] most remain concentrated in annual and monthly cycles contracts. Compared with developed economies (Neuhoff et al., 2023), China's share of multi-year green power contracts remains relatively low.

This reflects the need for further development in China's electricity market, particularly in developing long-term price stabilization mechanisms and hedging instruments. However, as the national focus on carbon emissions continues to increase and society's emphasis on sustainable development goals grows, the demand for green electricity among enterprises is expected

[7] According to the National Electricity Market Trading Profile published by the China Electricity Council, green power traded within the province amounted to 204.8 billion kWh in 2024, up 281% from the volume traded in 2013 (53.77 billion kWh). The share of green power traded in provincial electricity transactions also increased, from 1% in 2023 to 4% in 2024.

to keep rising. Long-term green electricity trading, as a transaction method that can meet electricity users' need for stable, long-term green power, is significant for advancing the green transformation of businesses.

4.3.3 Waste utilization

(1) Organic fertilizer and biogas

In the agrifood system, waste utilization is an important topic. Among various types of waste, crop residues, livestock and poultry manure, and food waste have significant potential for energy and fertilizer.

Crop residues, as a multifunctional resource, have diverse and valuable applications. Beyond their use in energy production and as fertilizer, highlighted in this section, crop residues also serve as animal feed, providing a nutritional supplement for livestock. Additionally, they are commonly used as a substrate for mushroom cultivation, promoting the development of the mushroom industry and are raw materials for various industries, including construction materials, chemicals, and paper production.[8]

Since 2016, national policies have emphasized the comprehensive utilization of crop residues under the principle of "agriculture-first", aiming to increase soil organic matter and fostering circular agriculture. This reflects the importance the state attaches to the improvement of arable land quality, and also reflects both the government's commitment to improving arable land quality and its broader push for sustainable agricultural development.

At the national level, the crop residue policy targets resource-abundant regions, promoting the establishment of key counties for integrated crop residue utilization. The 2023 policy initiative marked a new stage in the sector's development. Locally, subsidy policies exhibit regional variation to reflect diverse agricultural contexts. For instance, Heilongjiang Province, a major producer of corn and rice, extends subsidies to agricultural social service providers and growers involved in straw return-to-field practices, reinforcing the role of straw in sustainable farming. In contrast, Shanghai's subsidy policy supports the comprehensive utilization of crop residues from rice, rapeseed, wheat, fresh corn, wild rice, and other crops. It encourages both in-field mechanized return and off-farm procurement and processing, thereby advancing diversified residue utilization. These differentiated subsidy policies reflect local agricultural resources and environmental conditions, providing a robust policy framework for the effective crop residue resource use.

Compared with the recycling of crop residues, utilizing livestock and poultry manure as fertilizer faces greater logistical challenges. This stems largely from China's agricultural pattern of spatial separation between farming and livestock production (Bai et al., 2022). To address this, since 2021 the government has implemented pilot projects promoting county-level resource utilization of livestock and poultry manure, especially in large grain-producing counties or those with substantial livestock resources and ecological significance.

The policy primarily supports enterprises focused on manure collection and treatment (excluding breeding enterprises), cooperatives, and socialized service organizations engaged in manure return. Local governments have tailored farming-recycling models based on actual capacity and manure utilization potential. A notable example is Zhucheng County in Weifang City, Shandong Province, which developed two manure cycling models: the "bidirectional small-scale circulation model between farms" and the "regional multi-directional medium-scale circulation model," based on the size and distribution of its livestock sector. Building on this foundation, Zhucheng also integrated a real-time information platform to create an "all-domain three-dimensional large-scale circulation model" across the entire county, enabling efficient resource allocation and use of manure.[9]

From an industrial chain perspective, crop residues and livestock manure can be converted into organic fertilizer via aerobic composting or anaerobic fermentation. Anaerobic fermentation not only produces biogas, a clean energy source, but also generates nutrient-rich organic fertilizer as a by-product. Biogas

[8] According to the National Report on Comprehensive Utilization of Crop Straw released by the Ministry of Agriculture and Rural Development, 647 million tonnes of crop straw were utilized nationwide in 2021. Among them, the amount of straw returned to the field reaches 400 million tonnes, the amount of feed utilization reaches 132 million tonnes, the amount of fuel utilization stabilizes at more than 60 million tonnes, and the amount of base material and raw material utilization reaches 12.08 million tonnes.

[9] Related information can be found at http://www.ghs.moa.gov.cn/gzdt/202203/t20220314_6392170.htm.

offers several advantages: it is clean, environmentally friendly, renewable, and has a high energy density, making it easy to store and transport. In daily life, biogas can be used for cooking, heating, lighting, providing a cost-effective and accessible energy solution. In industry, biogas serves as a green alternative to fossil fuels, applicable in power generation, chemicals, and transportation, thereby reducing greenhouse gas emissions and advancing a greener energy mix. At the same time, the digestate produced from anaerobic fermentation can be further processed into high-quality organic fertilizer. This organic fertilizer is rich in essential nutrients like nitrogen, phosphorus, potassium and other nutrients needed for plant growth, as well as organic matter and microbial communities. Its application can significantly improve soil structure, increase soil fertility, and promote healthier and more productive crop growth (see Box 4-3).

Box 4.3 Resource Utilization of Agricultural Waste

Basic information

Qingtongxia in Ningxia Hui Autonomous Region, produces rice, wheat, corn, apples, grapes and other crops. In recent years, Qingtongxia has relied on leading enterprises to set up an agricultural biomass technology innovation center, and promoted the recycling of livestock and poultry breeding manure, crop straws and other wastes throughout the chain, forming a model of agricultural waste resource utilization that integrates the collection of agricultural wastes, biogas energy development and utilization, biomass pellet fuel processing, and clean gas supply and heating services.

Main practices

Qingtongxia has established a centralized third-party collection and treatment center for agricultural waste, emphasizing the comprehensive utilization of agricultural residues and the development of renewable clean energy. Additionally, it has standardized the production activities of leading agricultural enterprises, farmers' cooperatives, and large-scale farms, thereby promoting the enhancement of green practices and the implementation of sustainable circular development.

Following the approach of "building one center, cultivating two systems, and establishing three factories," Qingtongxia has adopted a "government project-driven + enterprise investment" model to create a center for the resource utilization of agricultural waste, an agricultural waste collection and transportation system, biogas plants, biomass pellet fuel factories, and organic fertilizer plants. This has created a comprehensive sustainable circular development model that integrates biogas projects (combined heat and power), organic fertilizer processing, green production, and the circular development of planting and breeding. Additionally, it includes biomass pellet fuel production and clean heating, facilitating the efficient conversion of agricultural waste.

Qingtongxia has established an agricultural waste collection and transportation system, where biogas plants, biomass pellet fuel factories, and organic fertilizer plants classify and process the collected livestock manure, crop residues, and forestry by-products. Each year, approximately 100,000 tonnes of livestock manure, 20,000 tonnes of crop residues, and 60,000 tonnes of forestry by-products are collected and processed.

Achievements

The comprehensive utilization rate of livestock manure exceeds 99%, while the utilization rate of crop straw reaches over 91%. The area dedicated to organic fertilizer application has reached 180,000 acres, and the organic matter content in the soil has increased by over 3%.

The treatment center annually supplies 50,000 tonnes of liquid fertilizer and 30,000 tonnes of solid organic fertilizer to nearby planting bases for wine grapes, goji berries, and rice. It also provides residential gas to 2,000 households in the ecological relocation area and transmits 8 million kilowatt-hours of clean electricity to the national power grid. Utilizing biomass pellet fuel, it offers clean heating services covering approximately 500,000 square meters to various towns and schools.

The development of biomass energy promotes the treatment of agricultural waste, replacing approximately 28,600 tonnes of standard coal each year and reducing carbon emissions by 19,100 tonnes. This initiative supports sustainable agricultural development and contributes to carbon reduction efforts.

Source: http://www.ghs.moa.gov.cn/gzdt/202205/t20220526_6400497.htm

In the process of resource utilization, kitchen waste is mainly transformed into three types of products, including crude oil and grease, biogas, and organic fertilizer. Among them, the use of biogas and organic fertilizer is consistent with the resource recovery pathways discussed earlier for crop residues and livestock and poultry manure. Crude oil and grease, after appropriate refining, can be converted into biodiesel or serve as industrial raw materials, thereby offering new resource streams for the energy and chemical industries.

China began its exploration of food waste resource utilization in 2010, aiming to fundamentally address food safety issues associated with "gutter oil" and "garbage pigs." To tackle these problems effectively, the central government designated 33 representative cities as the first batch of pilot cities for the resource recovery and safe treatment of kitchen waste. These cities actively adopted advanced biotechnologies and environmental management practices, seeking to transform kitchen waste into valuable resources.

Following five rounds of pilot programs involving a total of 100 cities, China has achieved remarkable progress in the resource utilization and safe disposal of kitchen waste. Through continuous innovation and practical experience, pilot cities have not only achieved effective treatment of kitchen waste but also successfully converted it into resource-based products with real market value.[10]

Building on these achievements, the government has extended its focus to rural areas, aiming to promote the resource utilization of rural household waste. In 2017 and 2020, two batches of 141 counties were selected as demonstration sites to carry out in-depth pilot projects. These counties have closely aligned their efforts with local realities, actively exploring and implementing a series of new kitchen waste utilization models tailored to rural conditions (see Box 4-4).

Box 4.4 Resource Utilization of Rural Domestic Waste

Basic information

Since June 2017, Xiangshan County in Ningbo City, Zhejiang Province, has been listed among the first 100 demonstration counties for the classification and resource utilization of rural household waste. The county has embraced the goals of "reduction, resource utilization, and harmlessness," adapting to local conditions, innovating models, and optimizing management. This approach has led to a low-cost, replicable, and sustainable development path unique to Xiangshan, significantly enhancing the rural living environment.

To date, the county has implemented waste classification in 490 rural villages, achieving a coverage rate of 100%, a resource utilization rate of 100%, and a harmless treatment rate of 100%. Additionally, it has established 9 provincial-level high-standard demonstration villages, 6 municipal-level demonstration townships, and 21 municipal-level demonstration villages.

Typical experience

To implement effective garbage classification, source management is essential. Xiangshan County has innovated its management model to achieve this. Townships and administrative villages have established rules and regulations, including health assessment systems and methods for managing cleaning staff. By overseeing volunteer supervisors and utilizing community feedback mechanisms, such as "villagers say" assessments, the county continually enhances participation in garbage classification and improves the accuracy of classification rates.

To address the critical point of waste classification and transportation, the county has implemented "round-the-clock" cleaning requirements and established a four-category waste collection system, which classifies and processes kitchen waste, recyclables, general waste, and hazardous waste. In Xili Fang Village, for example, each garbage collection point features neatly organized bins in green, blue, red, and black. Detailed instructions are posted on each bin: green for food waste like peels and leaves, red for hazardous waste such as batteries, blue for recyclables, and black for other garbage.

This "four-category" system has significantly reduced daily garbage transport in Xili Fang Village from 2 tonnes to 0.5 tonnes, lowering transportation costs and landfill volume while preventing secondary pollution from centralized sorting. Additionally, food waste is digested on-site; the village has built a sunroom for fermenting food waste into organic fertilizer. This sunroom can produce nearly 100 tonnes of organic fertilizer annually, which is sold at a lower price to local growers.

To achieve the county-wide goal of reducing on-site, fully degradable rural waste, innovative recycling and treatment strategies have been implemented. By tailoring solutions to the geographical distribution and industrial characteristics of various townships and subdistricts, the county has established diversified terminal treatment systems to ensure comprehensive coverage.

[10] Source: https://www.ndrc.gov.cn/fggz/hjyzy/zyzhlyhxhjj/202006/t20200615_1315375_ext.html

Key Initiatives:

1. Solar Composting House Optimization

Redesigned and upgraded 228 decentralized solar composting facilities under a "retain, improve, or dismantle" principle.

Built 14 centralized eco-treatment centers using a township-consolidated model, adopting "mechanical dewatering & shredding + static aerobic composting" technology to shorten composting cycles from 6 months to 40 days.

2. Mechanical Rapid Composting Expansion

Established 9 mechanical composting terminals, including 2 township-consolidated facilities, to accelerate organic waste conversion.

3. Pioneering Biogas Anaerobic Fermentation

Piloted in Yangbei Village (Qiangtou Town), this method offers shorter processing cycles, higher fertilizer quality, and zero land occupancy, demonstrating promising trial results.

By integrating geographically adaptive technologies and scalable models, the county balances efficiency with sustainability, setting a replicable benchmark for rural waste management.

Source: http://www.moa.gov.cn/xw/qg/201912/t20191224_6333843.htm

(2) Advanced biofuels and power generation

From the perspective of energy utilization, waste in the agrifood system serves as a raw material for advanced biofuels (Qi et al., 2024). Leveraging technologies from physics, chemistry, and biology, these wastes can be efficiently converted into gaseous or liquid biofuels, including biogas, bioethanol, biodiesel, renewable methanol, and sustainable aviation fuel. Technological innovation plays a crucial role in driving the development of the biofuel industry. Currently, China has implemented a series of supportive policies and measures aimed at promoting technological research and development, as well as widespread application in the biofuels sector,[11] rather than mandating the use of biofuels in specific areas.

However, stronger global support for the biofuels industry has created a broad market for the industry's continued expansion.[12] Customs statistics indicate that China's exports of products under HS code 151800,[13] used as feedstock for biofuels, have risen steadily since 2015, with growth accelerating after 2021. To ensure a stable domestic supply of raw materials for its biofuel sector, the Ministry of Finance and the State Administration of Taxation have jointly announced that as of December 1, 2024, the 13% export tax rebate for waste cooking oil under HS Code 151800 will be officially abolished. Both international and domestic policy trends suggest an increasingly favorable environment for energy recovery from agrifood waste, pointing to strong growth prospect for the sector.

Power generation is another pathway for converting agrifood system waste into usable energy. Crop residues, livestock and poultry manure, and kitchen wastes can be processed by anaerobic fermentation to produce biogas, which is then used to generate electricity. Among these, crop residues offer the most diversified applications in power generation. On the one hand, they can be can be gasified for electricity production: under low-oxygen conditions, crop residues undergo chemical reactions that produce clean, energy-dense gases suitable for power generation. On the other hand, crop residues can also be directly combusted to produce electricity. Compared to gasification, direct combustion is a simpler and more widely scalable, particularly when paired with modern combustion technologies and equipment to improve efficiency.

In response to the rapid growth of the renewable

[11] Typical policies such as the "14th Five-Year Plan" for a modern energy system released in 2022 calls for the vigorous development of non-food biofuels such as biodiesel, and the "14th Five-Year Plan" for the development of renewable energy proposes to "support biodiesel, biojet fuel and other fields". The "14th Five-Year Plan" for Renewable Energy Development proposes to "support the R&D and popularization of advanced technology and equipment in the fields of biodiesel and bio-jet kerosene".

[12] The European Union has adopted the "ReFuelEU Aviation Regulation", which mandates that the fuel used in EU airports must be blended with 2% sustainable aviation fuel (SAF) from 2025 onwards, and also makes certain requirements on the technology route adopted for SAF. In addition to the European Union, the United Kingdom, the United States, Japan and South Korea and other countries are also actively promoting the development of the biofuel industry. The UK plans to implement the SAF Directive from January 1, 2025, the U.S. has released the U.S. Aviation Industry Climate Action Plan, Japan has set a target of 10% of aviation fuel to be used in SAF by 2030, and South Korea has mandated that all international flights departing from South Korea from 2027 onwards must be blended with SAF for refueling.

[13] HS code 151800 products include chemically modified, boiled, oxidized, dehydrated, blown or polymerized animal or vegetable fats and oils and fractions thereof, and also inedible mixtures or preparations of these fats and oils.

energy sector, China introduced a series of policy adjustments to its biomass power generation subsidy program in 2020.[14] For existing projects listed under the national renewable energy subsidy scheme, electricity generation beyond the project's full life-cycle quota is no longer eligible for central government subsidies. Instead, such projects will receive green certificates, allowing them to participate in the green certificate trading market. Additionally, once a biomass power project has been connected to the grid for 15 years—regardless of whether it has reached its full subsidy quota—it will cease to receive central government subsidies and transition fully into green certificate trading.

For newly approved biomass power projects, subsidies will be shared between the central and local governments, with the distribution ratio determined based on regional conditions. Importantly, the central government's contribution to these subsidies will be gradually reduced, implementing an orderly exit mechanism. While these policy changes are aimed at enhancing market efficiency, the gradual withdrawal of state subsidies may reduce the profitability of biomass power enterprises. This, in turn, could impact the upstream waste treatment segment of the agrifood system that provides raw materials for biomass energy production.

4.4 Scenarios and Simulations of Energy Transition in the Agrifood System

The future energy transition of the agrifood system will mainly rely on improving energy efficiency while increasing the proportion of non-fossil energy.[15] Based on the ratio of energy consumption per unit of output value and the proportion of non-fossil energy use, we developed differentiated emission reduction pathways, including a baseline scenario, a low-emission reduction scenario, a medium-emission reduction scenario, and a high-emission reduction scenario. We used the CAU-AFS model to predict the future GHG emissions from energy consumption in the agrifood system. The details of the modeling scenario design are presented in Table 4-1.

Table 4-1 Simulation Scenarios for Energy Transition in the Agrifood System

Scenario	Energy efficiency	Proportion of non-fossil energy
Baseline scenario	From 2026 to 2035, energy consumption per 10,000 yuan of GDP decreases by 1% per year, achieving a total reduction of 17.5% by 2035 and 35.8% by 2060.	The proportion is set at 20% in 2025, increasing by 0.5% per year to reach 25% in 2035 and 37.5% by 2060.
Low-emission reduction scenario	From 2026 to 2035, there is no decrease in energy consumption per 10,000 tonnes of GDP.	The proportion is set at 20% in 2025, and there will be no increase in this proportion thereafter.
Medium-emission reduction scenario	From 2026 to 2035, energy consumption per 10,000 yuan of GDP decreases by 1.5% per year, achieving a total reduction of 21.5% by 2035 and 46.3% by 2060.	The proportion is set at 20% in 2025, increasing by 1.3% per year to reach 33% in 2035 and 65.5% in 2060.
High-emission reduction scenario	From 2026 to 2035, energy consumption per 10,000 yuan of GDP decreases by 2% per year, achieving a total reduction of 25.5% by 2035 and 55% by 2060.	The proportion is set at 20% in 2025, increasing by 1.7% per year to reach 37% in 2035 and 79.5% in 2060.

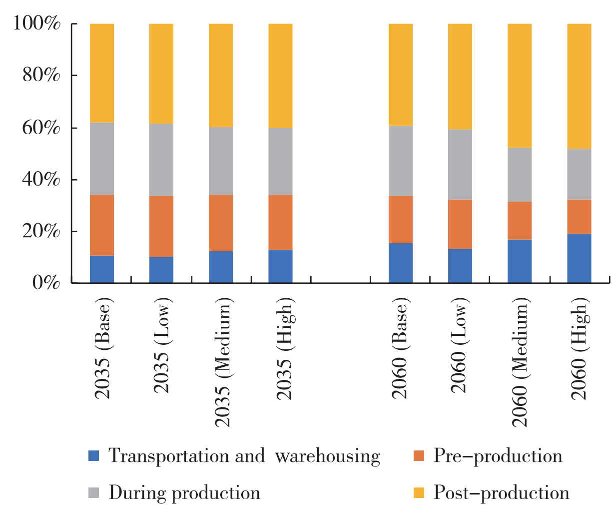
[14] This includes the Implementation Plan for Improving the Construction and Operation of Biomass Power Generation Projects issued by the National Development and Reform Commission (NDRC), as well as Several Opinions on Promoting the Healthy Development of Non-Water Renewable Energy Power Generation and Supplementary Circular on Matters Relating to Some Opinions on Promoting the Healthy Development of Non-Water Renewable Energy Power Generation, issued by the Ministry of Finance and other ministries and commissions.

[15] Fossil fuels include coal, oil and natural gas.

Compared to the 673 million tonnes of GHG emissions from the agrifood system in 2022, the projections show an upward trend in GHG emissions from the system through 2035 under various emission reduction scenario assumptions. Specifically, emissions are projected to climb to 815 million tonnes under the baseline scenario, and 940 million tonnes, 752 million tonnes, and 692 million tonnes under the low, medium, and high scenarios, respectively. Looking forward to 2060, emissions under the baseline and low scenarios are projected to grow further, to 850 million tonnes and 1,398 million tonnes, respectively. In contrast, the medium and high scenarios show significant reductions in emissions, effectively curbing the growth trend. In the medium scenario, emissions are projected to fall to 590 million tonnes, a 31% decrease compared with the baseline scenario, while in the high scenario, emissions are projected to fall further to 396 million tonnes, representing a 53% decrease.

In terms of the dynamic evolution of the emission structure, the share of GHG emissions from each stage of the agrifood system shows a high degree of consistency across the different mitigation scenarios up to 2035, with the differences from the baseline scenario within ±3% (see Figure 4-9). This indicates that the intensity of short-term emission reduction strategies has limited impact on the structural composition of emissions. However, by 2060, more pronounced structural shifts emerge. While the emission shares across stages under the baseline and low scenarios still differ by no more than ±3%, the medium and high reduction scenarios exhibit more significant deviations. Compared with the baseline scenario, the shares of pre-production and production in the medium scenario decrease by 3.5% and 6.1%, while the shares of transportation and storage and post-production increase by 1.6% and 8.0%, respectively; and the shares of pre-production and production in the high scenario decrease by 4.6% and 7.4%, while the shares of transportation and storage and post-production increase by 3.4% and 8.5%, respectively. These shifts result in a reordering of emission contributions: while the transportation and storage sector has the lowest share of emissions under the baseline scenario, the pre-production sector drops to the lowest under both the medium and high scenarios.

Figure 4-9 Greenhouse Gas Emissions structure under different emission reduction scenarios



Data source: CAU-AFS model

4.5 Conclusion and Policy Recommendations

This chapter analyzes the energy consumption and GHG emissions of China's agrifood system, and accordingly explores its energy transition pathway, which follows the principles of "cleaner substitution, energy efficiency enhancement and recycling". Specifically, the transition pathway can be discussed from the following aspects:

First, electricity, as an indispensable energy carrier in the agrifood system, plays a crucial role in reducing emissions across various stages of the system.

By promoting the transition to clean electricity, GHG emissions in production, processing, transportation, and other stages of the agrifood system can be significantly reduced.

Second, in the production stage, energy transition is driven by both demand and supply forces. On the demand side, increasing the electrification of agricultural machinery can enhance production efficiency and simultaneously reduce overall energy consumption. On the supply side, the development of distributed renewable energy in rural areas, together with the construction of smart microgrids, can establish an integrated "new energy + industry" development model, providing strong support for the sustainable transformation of the agrifood system.

Third, the energy transition of the pre-and post-production stages can draw on the valuable lessons from the industrial and commercial sectors. Improving energy efficiency and increasing the proportion of renewable energy can directly drive transitions in these stages. At the same time, stakeholders in the system should actively monitor carbon emissions and prepare for future participation in carbon markets, promoting transitions through market-based mechanisms.

Finally, waste plays a crucial role in the energy transition of the agrifood system. As an important raw material for renewable energy production, waste can be converted into energy while also replacing chemical fertilizers through organic waste recycling. This resource conversion constitutes a key link in the circular agrifood system, helping to close material and energy loops and advancing sustainability.

However, the road to energy transition in the agrifood system is not straightforward and faces a number of systemic challenges that require targeted policy interventions:

1. Cross-sectoral policy fragmentation

Energy transition in the agrifood system is a multidimensional and cross-sectoral endeavor that involves agriculture, industry, energy, and environmental protection. These sectors often have distinct policy goals, leading to conflicts during implementation. For example, improving energy efficiency may conflict with food security goals if key technologies are not yet economically viable. Addressing these tensions requires integrated policy instruments and innovative mechanisms to promote coordination. Breaking down sectoral silos and establishing a cross-sectoral governance framework will facilitate resource sharing and coherent policy implementation.

2. Technological development and diffusion

Key technologies must be not only efficient and environmentally sound but also adaptable to regional differences in natural resources, ecological conditions, and economic development. However, technology diffusion faces the challenge of "diseconomies of scale." Smallholders and enterprises often lack the capital and risk tolerance to adopt new technologies. A comprehensive technology support system should be established, consisting of:

● Basic research: Focus on common technical challenges such as biomass conversion and smart agricultural equipment.

● Regional adaptation: Develop localized, cost-effective solutions based on local resource and ecological conditions.

● Application and promotion: Adopt differentiated strategies—market-driven promotion for large farms and enterprises (e.g., through equipment financing), and targeted subsidies, training, and technical services for smallholders. Cooperatives and service providers can also help lower the adoption threshold.

3. Information constraints

A lack of accessible information hampers the enthusiasm and capacity of stakeholders—including farmers, cooperatives, and agribusinesses—to participate in energy transition. Many are unfamiliar with emerging mechanisms like green power trading or carbon markets. A specialized digital platform should be created to support energy transition, integrating modules for:

● Policy interpretation: Real-time updates on national and local energy policies.

● Technology guidance: Detailed introductions and case studies on various energy solutions.

● Best practices: Data-driven analysis and AI-powered recommendations based on successful implementation cases.

4. Weak incentive mechanisms

Despite progress in green development, the agricultural sector's participation in China's Certified Voluntary Emission Reductions (CCERs) is limited, and the methodology system remains underdeveloped. A dedicated carbon sink methodology system covering planting, livestock, and waste management should be established. This will enable accurate quantification and certification of emission reductions. Additionally, an "agricultural carbon credit" mechanism could be explored to recognize and reward small-scale emissions reductions by farmers. Integrating these credits into regional carbon markets would provide economic incentives and raise societal awareness of low-carbon agriculture.

5. International cooperation

Global collaboration is essential for accelerating the agrifood system's energy transition. A bidirectional technology cooperation network should be established, along with alignment to international regulatory frameworks. An international R&D program can focus on biomass and smart agricultural machinery, while a "South-South Cooperation" platform could facilitate the export of technologies such as photovoltaic agriculture and biogas systems. Monitoring global policy developments—including the Paris Agreement, SDG implementation, and carbon market trends—can help align domestic strategies with international standards. Active participation in global governance through partnerships with FAO, IEA, and others can enhance China's voice and contributions to the global low-carbon transition.

Reference

Bai, Z., Fan, X., Jin, X. *et al.*, 2022. Relocate 10 Billion Livestock to Reduce Harmful Nitrogen Pollution Exposure for 90% of China's Population. *Nature Food* 3, 152-160.

Bian, S., Yang, S., Yang, X. *et al.*, 2024. Strategies to Improve China's Carbon Accounting System under International Green Trade Barriers. *Strategic Study of CAE* 26(4), 96-107.

Brenna, M., Foiadelli, F., Leone, C., Longo, M., Zaninelli, D., 2018. Feasibility Proposal for Heavy Duty Farm Tractor. Presented at the 2018 International Conference of Electrical and Electronic Technologies for Automotive, IEEE, 1-6.

Cao, X., Sun, B., Chen, H. *et al.*, 2021.Approaches and Research Progresses of Marginal Land Productivity Expansion and Ecological Benefit Improvement in China. *Bulletin of Chinese Academy of Sciences* 36(3), 336-348.

FAO, 2021. The Share of Food Systems in Total Greenhouse Gas Emissions. Global, Regional and Country Trends, 1990-2019. FAOSTAT Analytical Brief Series No. 31. Rome.

Flint, J., Zhang, D., Xu, P., 2014. Preliminary Market Analysis for a New Hybrid Electric Farm Tractor. Presented at the 2014 International Conference on Global Economy, Commerce and Service Science (GECSS-14), Atlantis Press, 98-102.

Gao, H., Xue, J., 2020. Modeling and Economic Assessment of Electric Transformation of Agricultural Tractors Fueled with Diesel. *Sustainable Energy Technologies and Assessments* 39, 100697.

Henderson-Sellers, A., McGuffie, K., 2012. *The Future of the World's Climate*. Elsevier Science.

IRENA, FAO, 2021. Renewable Energy for Agrifood Systems: Towards the Sustainable Development Goals and the Paris agreement. Abu Dhabi and Rome.

Jin, S., Lin, Y., Niu, K., 2021. Driving Green Transformation of Agriculture with Low Carbon: Characteristics of Agricultural Carbon Emissions and Its Emission Reduction Path in Chin. *Reform* 5, 29-37.

Li, H., Song, F., Xia, F., 2024. Speeding up Renewable Energy Integration with Invisible Hands: Ancillary Service Market and the COVID-19 Natural Experiment. *The Energy Journal* 45(5), 1-31.

Morawicki, R.O., Hager, T., 2014. Energy and Greenhouse Gases Footprint of Food Processing, Editor(s): Van Alfen, N. K. *Encyclopedia of Agriculture and Food Systems*. Academic Press.

Neuhoff, K., Richstein, J.C., Kröger, M., 2023. Reacting to Changing Paradigms: How and Why to Reform Electricity Markets. *Energy Policy* 180, 113691.

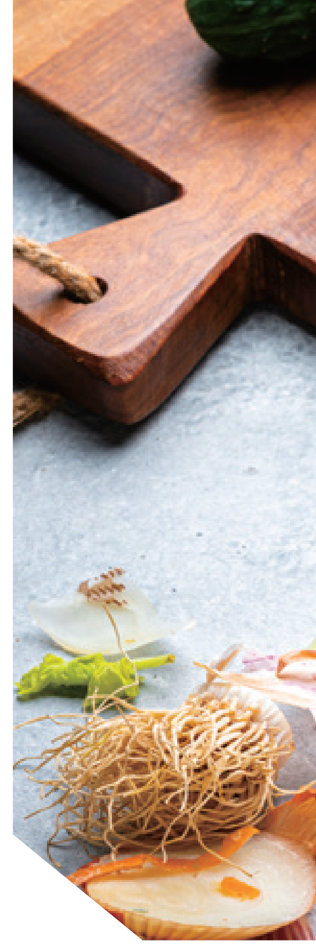
Qi, X., Qiu, B., Fu, J., 2024 New Implementation Pathways for the Resource Utilization of Agricultural Wastes under the Goal of Carbon Peaking and Carbon Neutrality. *Journal of Agricultural Resources and Environment* 41(5), 989-990.

Ren, M., Huang, C., Wu, Y. *et al.*, 2023. Enhanced Food System Efficiency Is the Key to China's 2060 Carbon Neutrality Target. *Nature Food* 4, 552-564.

Scolaro, E., Beligoj, M., Estevez, M.P., Alberti, L., Renzi, M., Mattetti, M., 2021. Electrification of Agricultural Machinery: A Review. *IEEE Access* 9, 164520-164541.

Ueka, Y., Yamashita, J., Sato, K., Doi, Y., 2013. Study on the Development of the Electric Tractor: Specifications and Traveling and Tilling Performance of a Prototype Electric Tractor. *Engineering in Agriculture, Environment and Food* 6(4), 160-164.

Wu, B., Wang, Y., Dai, Y. *et al.*, 2021. Current Status and Future Prospective of Bio-ethanol Industry in China. *Renewable and Sustainable Energy Reviews* 145, 111079.



Chapter 5

Carbon Mitigation Potential and Pathways of Food Loss and Waste Reduction in China

Li Xue[1,2], Shengkui Cheng[3], Gang Liu[4], Jingjing Wang[1,2], Hao Fan[2], and Ran Niu[2]

1. Academy of Global Food Economics and Policy, China Agricultural University
2. College of Economics and Management, China Agricultural University
3. Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Science
4. College of Urban and Environmental Sciences, Peking University

Key Findings

● First, food loss and waste (FLW) across different stages of the food supply chain in China exhibit distinct characteristics. The primary losses occur at the post-harvest handling (41.6%), followed by production (22.7%), and consumption (19.6%) stages, which collectively account for over 80% of the total FLW. Fruits and vegetables, due to their perishable nature, suffer a higher proportion of loss and waste compared to other food categories.

● Second, reducing food waste has a significant carbon emission reduction effect, with the most pronounced impact observed at the consumption stage. The carbon emissions resulting from FLW account for approximately 4% of China's total carbon emissions. Halving food waste at the consumption stage alone could realize more than half of the emission reduction potential, a figure significantly higher than at other stages. This highlights the critical role of changes in public consumption behavior and optimization of the food service system in driving a green and low-carbon transition.

● Third, China has largely established a food loss and waste reduction policy framework that covers the entire supply chain, although further improvements are needed. The system, centered around the "Anti-Food Waste Law" and various action plans, combines legal constraints, standard guidance, and technical support. While the current policy framework covers all stages of the supply chain, further refinement is required in terms of standardization, supporting measures, and regulatory enforcement. Establishing a long-term, effective mechanism for FLW reduction across all supply chain stages is essential to enhancing overall management efficiency.

Policy Recommendations

● First, establishing a collaborative food loss reduction system across the entire supply chain is essential. From a systems perspective, the food supply chain should be optimized by strengthening cold chain infrastructure, promoting digital transformation, improving loss reduction standards, and optimizing regional layouts. These measures will enhance the loss reduction capacity in the upstream and midstream stages, while simultaneously balancing carbon emissions and resource efficiency, thereby promoting a synergistic effect between loss reduction and carbon mitigation.

● Second, shifting consumer behavior to eliminate food waste is crucial. Targeting end-user stages such as food service and household consumption, policy guidance, information disclosure, educational campaigns, and technical support should be employed to encourage the public to develop habits of resource-efficient consumption. Embedding conservation practices into daily routines will help foster a social norm of sustainable consumption.

● Third, a multifaceted policy support and legal protection mechanism must be strengthened. Building on existing legal and policy frameworks, a cross-departmental collaborative governance system should be established, alongside enhanced legal safeguards and fiscal incentive mechanisms. A FLW monitoring and evaluation system should be put in place. Furthermore, the governance of FLW should be integrated into national climate targets and food security strategies, including incorporating it into Nationally Determined Contributions (NDCs) under global climate agreements. The potential to convert FLW reduction and emission reductions into carbon credits for carbon markets inclusion should also be considered. Additionally, China's experiences can be shared through South-South cooperation to support the sustainable development of global food systems.

5.1 Introduction

Amid the triple pressures of climate change, resource constraints, and population growth, promoting the green and low-carbon transformation of food systems has become a critical issue of global concern. Currently, food loss and waste (FLW) has emerged as a critical bottleneck hindering the sustainable development of the global food system. According to the Food and Agriculture Organization (FAO), post-harvest food loss in the global food system, up to the retail stage, accounts for approximately 14% of total production (FAO, 2019); The United Nations Environment Programme (UNEP) further states that food waste at the retail and consumption stages represents 17% of all food that is available for human consumption (UNEP, 2021). Consequently, reducing FLW has been incorporated into global policy agendas, with United Nations Sustainable Development Goal (SDG) 12.3 aiming to halve food waste at the retail and consumption stages and significantly reduce food loss in the supply chains by 2030.

The impacts of FLW extend beyond food itself, resulting in substantial resource depletion and environmental burdens. On the one hand, FLW results in inefficient use of natural resources, an especially pressing issue given global challenges such as hunger and malnutrition. According to the FAO, as of 2023, approximately 29% of the global population experienced moderate or severe food insecurity, with 733 million people facing hunger, an increase of 152 million people from 2019 (FAO, 2024). On the other hand, every step from farm to table consumes resources such as land, water, and energy, while simultaneously generating greenhouse gases (GHG) emissions. Wasted food, therefore, represents a hidden source of ineffective carbon emissions. Research indicates that in 2017, global FLW contributed to the emission of 9.3 billion tonnes of CO_2eq, accounting for approximately half of the global food system's carbon emissions that year. This scale is roughly equivalent to the combined annual emissions of the United States and the European Union. Halving global FLW could reduce carbon emissions from the food system by 25% (Zhu et al., 2023), highlighting the immense mitigation potential of tacking this issue.

Consequently, reducing FLW is widely seen as a key strategy for cutting carbon emission, improving resource utilization efficiency, and driving the sustainable transformation of food systems (Ren et al., 2023; Geyik et al., 2022; Alexander et al., 2017). In response, governments and international organizations have prioritized FLW reduction in their climate and sustainability agendas. For instance, the European Union's "Green Deal" outlines the "Farm to Fork Strategy", emphasizing FLW reduction as a critical pathway to achieving a healthy, fair, and sustainable food system. Similarly, the U.S. Department of Agriculture (USDA), the Environmental Protection Agency (EPA), and the Food and Drug Administration (FDA) have jointly issued the "National Strategy for Reducing Food Waste, Waste, and Organic Recycling", underscoring the multi-faceted economic, social, and environmental benefits of tackling food waste. These actions reflect the global significance of FLW management.

As one of the world's largest developing economies, China has made remarkable progress in ensuring food security. However, FLW remains a serious concern. With the continuous expansion of the food supply chain and the diversification of dietary preferences among urban and rural residents, FLW at post-harvest handling, transportation, distribution, and urban consumption stages have become increasingly prominent (Liu et al., 2013; Jiang et al., 2023; Lu et al., 2022; Cheng et al., 2012; Lu et al., 2019). According to the 2023 "Food and Nutrition Development Report" published by the Chinese Academy of Agricultural Sciences, FLW in China represented 1.88 trillion yuan in 2022, accounting for 22.3% of the total agricultural output value. Perishable foods such as vegetables and meat accounted for a particularly large share of this waste. Research has shown that the potential for reducing loss during the production and distribution of fresh produce such as cabbage and tomatoes can reach up to 60%, while the beef supply chain also has a reduction potential of over 10% (Lu et al., 2022; Long et al., 2025).

FLW not only exacerbates the environmental and resource burdens but also becomes a latent source of GHG emissions, posing a severe challenge to achieving China's "carbon peak and carbon neutrality" strategic goals. In response, the Chinese government has introduced a series of policy measures, including the "Anti-Food Waste Law of the People's Republic of China", the "Food Saving and Anti-Food Waste Action Plan", and the "14th Five-Year National Agricultural Green Development Plan". These policies emphasize "promoting food-saving actions" and "reducing food loss and waste" as key strategies for achieving a green and low-carbon transformation. Their ongoing implementation provides a solid institutional foundation for constructing a systematic governance framework for FLW.

In this context, it is urgently needed to evaluate the carbon reduction potential of addressing FLW in China's food system from a full supply chain perspective. By identifying key points for loss reduction and quantifying the carbon mitigation effects of various pathways, tailored strategies and policy recommendations can be developed that align with China's national circumstances. This will provide scientific support for the country's "dual carbon" strategic goals and serve as a crucial step in promoting a green and low-carbon food system, while advancing the broader goal of building a resource-efficient and environmentally sustainable society.

5.2 Current Status of Food Loss and Waste in China

5.2.1 Characteristics of Food Loss and Waste

As the world's largest agricultural producer and food consumer market, China feeds approximately 19% of the global population with less than 7% of the world's arable land, achieving the remarkable "Chinese Miracle". However, with ongoing economic development, changes in urban and rural dietary structures, and the extension of the supply chain, FLW have increasingly become prominent issues. These challenges now pose significant constraints on the efficient and sustainable operation of China's food system.

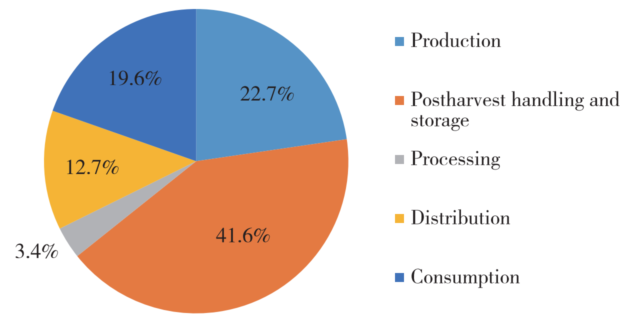
Drawing on existing domestic and international research on FLW in China (Xue et al., 2021) and incorporating the latest data on food production, import and export trade, this study employs the material flow analysis (MFA) method to systematically estimate the scale of FLW across China's entire food supply chain in 2023. The results show that FLW in China's food system exceeded 300 million tonnes in 2023, accounting for approximately 24.7% of the total food available for consumption. Excluding losses at the production stage, FLW from other stages still accounts for about 19% of the total edible food. These figures underscore the magnitude of the challenge and indicate that China continues to face severe FLW issues.

By stage, the majority of FLW occurs during post-harvest handling and storage stage, accounting for 41.6% of the total (Figure 1). Comparative international studies show that China's loss at this stage is much higher than those in industrialized countries such as the UK (4.8%) and Japan (10.5%) (Bräutigam et al., 2014; Liu et al., 2016). This suggests that there is significant potential for loss reduction at post-harvest stages in many developing countries, including China. Through the adoption of advanced threshing technologies and improved cold chain and storage infrastructure, substantial reductions in post-harvest losses can be achieved, leading to improvements in food system efficiency (Al-Khateeb et al., 2021; Jiang et al., 2023).

At the production stage, over 22% of food loss is attributed to mechanical damage, pests, and extreme weather events. Reducing these losses requires accelerating agricultural modernization, including improving the precision of sowing and harvesting machinery and enhancing agricultural disaster risk management capabilities, to reduce primary production losses (Lesk et al., 2016; Li et al., 2017).

The consumption stage also remains a critical point of concern, accounting for nearly 20% of total FLW. Notably, food waste from dining out contributes around 16%, far higher than the 4% observed in household dining. This disparity is closely related to cultural norms, such as frequent social dining and the traditional "face-saving" mindset that encourages excessive ordering. Therefore, enhancing public awareness of food conservation and promoting green practices within the food service industry are key strategies for reducing waste at the consumption end.

Figure 5-1 Proportion of Waste by Segment of Food Loss and Waste in China



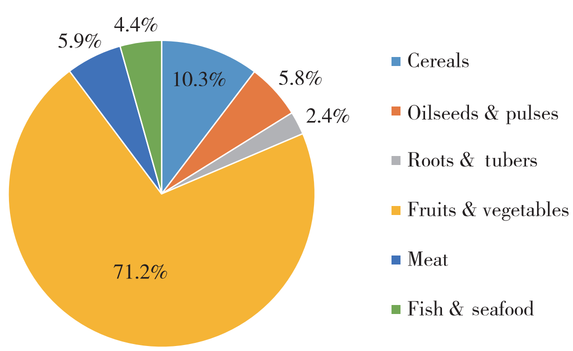
Data source: Xue et al. 2021

In terms of food categories, vegetables and fruits account for the largest share of FLW, representing over 70% of the total. These are followed by grains (10.3%) and meats (5.9%) (Figure 2). This indicates that the loss and waste of fruits and vegetables are central challenges within China's current FLW landscape. Further disaggregation by supply chain stages reveals that vegetables and fruits dominate the losses across all segments. Production, processing, transportation, retailing, and consumption comprise over 30% of losses at each stage. Particularly in the production and retailing stages, losses of fruits and vegetables exceed 80%, highlighting the significant pressure to reduce waste both upstream and downstream in the supply chain. This can be largely attributed to their biological characteristics: as high-moisture, perishable items, fruits and vegetables are highly susceptible to spoilage if not rapidly cooled, sorted, and properly stored after harvest.

In addition, consumer preferences play a substantial role in food waste. Consumers often favor visually pristine produce with bright colors, discarding items with minor blemishes or irregular shapes that are perceived as "inferior". This emphasis on appearance further exacerbates FLW at the retailing and consumption stages.

In summary, the high loss rate of fruits and vegetables highlights the significant impact of food category heterogeneity on shaping FLW patterns. To address these challenges, targeted interventions are needed, particularly in post-harvest pre-cooling, packaging optimization, logistics improvements, revision of retail appearance standards, and consumer education. These measures will be vital for curbing the waste of fruits and vegetables across the entire supply chain.

Figure 5-2 Proportion of Losses and Wastage of Various Types of Food in China



Data source: Xue et al. 2021

5.2.2 Regional Distribution Characteristics of Food Loss and Waste

From the perspective of urban-rural disparities, food waste at the consumption exhibits significant spatial and behavioral differences. Studies indicate that in 2023, the average daily food waste per capita in urban households was 15.47 grams, with vegetables accounting for the highest proportion at 47.45%, followed by staple foods (20.51%) and meats (13.41%).

The level and composition of waste also vary significantly across different dining scenarios: food waste per capita at meals was 10.70 grams, which is 2.24 times higher than that of food waste outside meals. Among food waste within meals, vegetables accounted for 55.39%, followed by staple foods (20.80%) and meats (18.72%); while waste outside meals was primarily composed of vegetables (29.65%), dairy products (25.68%), and fruits (21.67%) (Zhang et al., 2024). The result reflects the significant influence of household dining structures, food storage habits, and consumer preferences on food waste generation.

In contrast, rural households exhibit relatively lower levels of food waste, though the issue remains significant. It is estimated that the average edible food waste per meal per household is 8.74 grams, with vegetable waste accounting for nearly half of this amount. Based on this, it is estimated that rural residents waste approximately 21 kilograms of food per person annually (Li et al., 2021). While the absolute volume is smaller than that in urban areas, the cumulative effect remains substantial due to the large rural population. It is particularly true in the context of self-sufficiency in agricultural production and underdeveloped cold chain infrastructure, which contribute to heightened losses of perishable items like vegetables.

From a regional perspective, China's provinces display notable differences in both total volume and per capita levels of food waste. Overall, Guangdong, Jiangsu, Sichuan, Shandong, and Henan are the provinces with the highest total food waste. In 2018, Guangdong's food waste at the consumption stage reached 5.3 million tonnes, while Shandong and Henan exceeded 2.4 million tonnes, and Sichuan's food waste reached 4.18 million tonnes in 2020. In contrast, regions such as Tibet, Qinghai, and Ningxia exhibited the lowest levels of food waste, with differences reaching several orders of magnitude.

In terms of per capita food waste, coastal and economically developed regions were significantly ahead of central and western regions. Shanghai (58.75 kg per capita), Chongqing (52.73 kg per capita), and Tianjin (72.05 kg per capita) ranked among the highest nationwide, with Tianjin being particularly notable, as more than half of its food waste originated from tourism-related consumption. By comparison, Guizhou (28.56 kg per capita), Qinghai (28.54 kg per capita), and Guangxi (26.10 kg per capita) reported much lower per capita waste levels.

Interprovincial differences also exists in the types of food wasted. Vegetables are the most wasted food category across all regions, followed by grains (e.g., rice, wheat) and aquatic products. Coastal provinces such as Fujian, Shanghai, Zhejiang, and Jiangsu had significantly higher proportions of aquatic product waste compared to inland regions. In contrast, Tibet displayed higher waste proportions in animal and lower waste levels in vegetables and fruits. Due to their large population sizes and relatively high per capita waste levels, provinces such as Sichuan, Shandong, Jiangsu, and Hebei, are particularly affected by food waste (Ogunmoroti et al., 2022; Niu et al., 2022; Wang et al., 2021). Overall, food waste levels are positively correlated with population size, urbanization rates, and consumption capacity, particularly in highly urbanized provinces with thriving tourism industries.

The scale and structure of consumption end food waste in China are shaped by a combination of urban-rural consumption behaviors regional economic development, population density, dietary habits, and infrastructure conditions. Loss of perishable foods such as vegetables, fruits, and meats during production, post-harvest handling, processing, storage, and consumption are particularly severe. Out-of-home dining scenarios further exacerbate waste levels. Regionally, southeastern coastal areas generate significantly more total food waste than the less-developed central and western regions, exhibiting stark regional disparities.

As the world's largest food producer and consumer, China's FLW issue has significant implications for global food security and environmental sustainability, with considerable mitigation potential. Therefore, it is essential to formulate targeted intervention policies that account for urban-rural differences and regional structures. Such strategies should be region-specific, stage-specific, and food-type-specific. Multi-level and promote multi-level, differentiated loss reduction strategies tailored to local conditions can enhance resource utilization efficiency in the food system, improve carbon mitigation performance, and contribute meaningfully to global effort to reduce food waste and secure sustainable food systems.

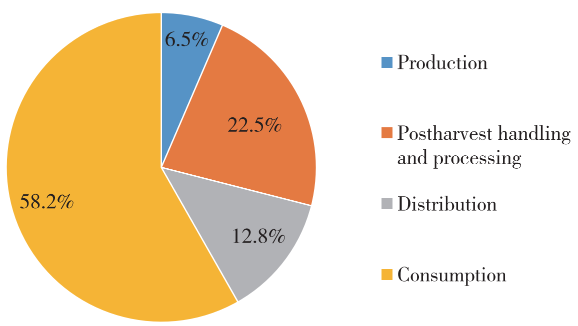
5.3 Environmental Impact of Food Loss and Waste

Based on the estimated scale of FLW across the entire food supply chain in China in 2023, combined with the carbon emission factor data by food type and supply chain stage, this study systematically assesses the environmental impact of FLW, particularly its carbon emission effects. The findings show that in 2023, total carbon emissions caused by FLW accounts for around 3.7% of China's total annual carbon emissions.

From the perspective of the supply chain, the carbon emission associated with FLW exhibit significant variations (Figure 3). Specifically, the consumption stage is the primary source, contributing over 50% of the total FLW-related emissions. The carbon emissions are not only limited to direct energy use during food consumption but also reflect the cumulative energy and resource inputs throughout the entire food production, processing, and distribution chain, further exacerbating the environmental burden. Notably, carbon emissions due to food waste in dining-out settings are significantly higher than those from household consumption, largely due to practices, such as excessive ordering and food preference based on appearance, which lead to increased waste in restaurants.

At other stages, emissions from the production stage account for approximately 6.5% of the total FLW-related carbon emissions, primarily arising from energy usage in agricultural production, fertilizer application, and machinery operations. Post-harvest handling and processing contribute about 22.5%, reflecting the critical role of the midstream stage in the carbon profile. The distribution stage accounts for 12.8%, primarily associated with energy consumption in food transportation and storage. These findings underscore the importance of reducing FLW, particularly at the consumption and midstream stages, is critical for advancing climate mitigation goals.

Figure 5-3 Carbon Footprint Ratio of Food Loss and Waste Sub-Segments in China



Data source: Xue et al. 2021

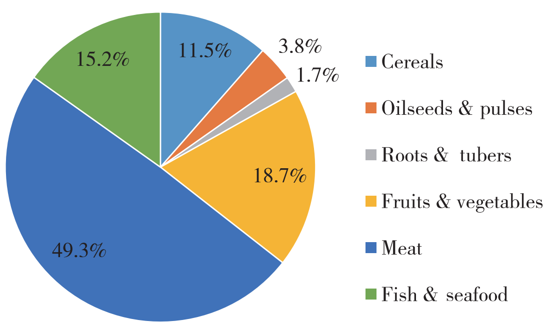
In terms of food types, meat loss and waste constitute the largest source of ineffective carbon emissions, contributing nearly 50% of the total. This is primarily due to the highly resource- and emission-intensive nature of meat production, which includes energy-intensive processes such as feed crop cultivation, livestock farming, and slaughter processing. As a result, meat waste carries a disproportionately large carbon footprint, making it a key focus for mitigation efforts.

Vegetables and fruits are the second largest source of ineffective carbon emissions, accounting for nearly 19% of the total emissions. Although their unit emission intensity is relatively low, the sheer volume of waste, particularly at the consumption stage, which account for approximately 47% of the related emissions, still generates a substantial environmental impact. Seafood follows closely, contributing about 15% of total emissions from FLW. The high carbon footprint of seafood stems from energy-intensive processes such as aquaculture, processing, and cold chain logistics, which involve substantial refrigeration and transport related energy consumption.

Grains account for 11.5% of total emissions, with emissions mainly concentrated at the consumption stage. These emissions not only result from direct food waste but also reflect the cumulative carbon footprint of production, processing, and transportation, reflecting the carbon load of the entire farm-to-table process. In contrast, the contributions from oilseeds and tubers are relatively small, representing 3.4% and 1.7% of total emissions, respectively, due to their relatively lower production-related carbon intensity.

In sum, differences in production methods, storage conditions, and consumption characteristics lead to varied emission profiles across food types. Meat, vegetables and fruits, and seafood are currently the three categories exerting the greatest carbon pressure. Targeted mitigation strategies, particularly those addressing consumption-stage waste, are therefore essential to reducing overall carbon emissions of the food system and contributing to climate change mitigation efforts (see Figure 4).

Figure 5-4 Carbon Footprint Proportion of Food Loss and Waste by Category in China



Data source: Xue et al. 2021

5.4 Carbon Emission Effects of Reducing Food Loss and Waste

5.4.1 Potential for Food Loss and Waste Mitigation

Reducing FLW presents significant potential for emissions reduction and resource conservation, and is one of the key pathways toward achieving green and low-carbon development goals. Through multidimensional coordinated interventions, it is possible to enhance resource efficiency, promote ecological environmental protection, and accelerate the achievement of the United Nations SDGs, particularly Target 12.3. Numerous studies and practices have shown that interventions such as technological innovation, packaging optimization, supply chain management, consumer education, and social participation mechanisms can yield tangible results across various stages of the supply chain, forming a systemic governance framework of "source prevention—process control—end-stage transformation".

At the technological level, innovations in preservation and storage have been proven to significantly reduce losses. For example, natural edible materials such as chitosan coatings can extend the shelf life of fruits and vegetables, reducing decay and disease by 30%-50%, while enhancing antioxidant properties (Romanazzi and Moumni, 2022). Cold chain packaging and multilayer composite materials can extend shelf life and reduce waste by approximately 10% (Brennan et al., 2021). Digital agriculture and intelligent logistics technologies, such as RFID tags, temperature control sensors, and food traceability systems, have proven effective in optimizing cold chain transportation and inventory management, reducing losses by 15%-30% (Benyam et al., 2021). The application of predictive models, dynamic monitoring, and refined sorting technologies in supply chains is also expected to reduce midstream losses by up to 30% (Ciccullo et al., 2021). In addition, in harvesting and distribution stages, the adoption of low-temperature harvesting, vacuum pre-cooling, and modified atmosphere packaging has reduced post-harvest losses by 30%-50% in developed countries (Elik et al., 2019), highlighting the loss reduction potential of integrated technologies.

On the consumer behavior front, raising public awareness about food conservation and encouraging sustainable consumption habits are crucial for reducing waste. Studies have found that approximately 60% of households report a reduction in waste after participating in food-saving initiatives, with high-income countries achieving reductions of 25%-30% (Zamri et al., 2020). Behavioral interventions, such as changing plate sizes, adjusting the order of meal service, and providing precise meal portioning, have been shown to reduce catering waste by up to 57% (Reynolds et al., 2019). Information reminders, nutrition education, and school-based intervention programs can reduce vegetable waste by up to 28%. Additionally, gamification interventions and community participation activities can enhance self-awareness and social responsibility, reducing waste by 7% and increasing conservation awareness by 19% (Soma et al., 2020), offering feasible pathways for the socialization and gamification of interventions.

At the level of social innovation, platform-based food redistribution mechanisms are emerging as effective tools for reducing waste. Food-sharing apps and community food banks, for example, connect surplus food resources across the supply chain with those in need, facilitating efficient redistribution from production to consumption (Harvey et al., 2020). These platforms not only effectively alleviate structural waste issues but also foster social equity and public welfare ecosystems.

In the context of China, the mitigation potential is equally substantial. It is estimated that food loss could be reduced by 8.75 billion kilograms annually, equivalent to the yearly food consumption of approximately 100 million people (Wang et al., 2021). Post-harvest to retail loss reduction potential in fresh produce like cabbage and tomatoes is estimated at 60% and 58.5%, respectively (Lu et al., 2022). The loss rate in the beef industry chain could be reduced from 23.83% to 13.55% (Long et al., 2025), and the potential reduction in the three main grains – rice, wheat, and maize – over the next decade could reach between 20 million and 95 million tonnes (Cao et al., 2024). However, to realize these potentials, a systematic and coordinated mechanism must be established, covering scientific research, policy support, standardization, public participation, and social innovation.

In summary, reducing FLW requires integrated efforts across multiple points in the supply chain, including source control, process optimization, and consumer guidance, strengthening the synergy between technology, behavior, and systems. For example, research indicates that by enhancing consumer education, promoting advanced packaging technologies, standardizing date labels, and establishing food service monitoring systems, the United States could reduce waste by 10%-15% annually (Read and Muth, 2021). For China, developing a robust policy system centered on food loss reduction will provide strong support for achieving climate change goals, ensuring food security, and promoting the green transformation of its food system.

5.4.2 Carbon Emission Reduction Effects of Mitigating Food Loss and Waste

(1) Scenario Design

To quantitatively assess the carbon mitigation potential of different food system strategies, this study develops a set of reduction scenarios based on material flow analysis (MFA) models. Drawing on existing research findings and focusing on key stages of FLW, the scenarios assume constant final food consumption levels. Each scenario includes three levels of intervention intensity, low, medium, and high, to capture the impact of varying degrees of intervention (Table 1):

1) Production, Postharvest Handling, and Processing Loss Scenarios: Prior studies highlight postharvest handling and processing as critical stages for food loss in China, often resulting from inadequate storage and transportation infrastructure, low processing efficiency, and substandard operational practices. Accordingly, three reduction scenarios are established, assuming a 10%, 25%, and 50% decrease in loss rates at this stage, to evaluate the carbon emission reduction potential from technical improvements and management optimization at these stages.

2) Transportation and Retailing Loss Scenarios: Research indicates that transportation and retailing stages are major sources of FLW, especially for perishable goods such as fruits and vegetables. Losses at these points are largely due to short shelf life, poor storage conditions, and insufficient cold chain coverage. This study simulates potential emission reductions under three levels of intervention, assuming 10%, 25%, and 50% loss reduction.

3) Consumption-Stage Waste Scenarios: SDG 12.3 calls for halving per capita food waste at the retail and consumer levels by 2030. Given that food waste at the consumption stage directly leads to upstream resource wastes, its reduction contributes meaningfully to lowering the overall carbon footprint. This study likewise adopts three reduction levels, 10%, 25%, and 50%, with the highest level aligning with the global SDG target to evaluate the emission reduction potential under strong-intervention scenarios.

Table 5-1 Scenario Design

Scenario Design		Percentage reduction (%)		
		Low	Middle	High
S1	Production	10	25	50
S2	Postharvest handling and storage	10	25	50
S3	Processing	10	25	50
S4	Distribution	10	25	50
S5	Consumption	10	25	50

(2) Results of Carbon Emission Reduction

The analysis reveals a clear inverse relationship between FLW and carbon emissions: as FLW decreases, emissions fall substantially. Specifically, a 50% reduction in food waste at the consumption stage yields the most significant carbon mitigation effect, achieving an approximately 31% reduction in total emissions relative to the baseline scenario. This highlights the pivotal role of end-consumer behavior in shaping the carbon profile of the food system.

The postharvest stage also offers considerable emission reduction potential. A 50% reduction in postharvest losses results in an estimated 8% decrease in carbon emissions. Although less impactful than reductions at the consumption stage, this stage still holds considerable value for targeted policy interventions through better storage, processing, and distribution.

Moreover, if losses in both postharvest and transportation/retailing stages are halved, the combined emission reduction effect is equivalent to a 25% reduction in consumption-stage waste, amounting to an approximate 15% decrease in carbon emissions. This demonstrates that coordinated interventions in upstream segments can produce meaningful synergistic mitigation outcomes (see Figure 5-5).

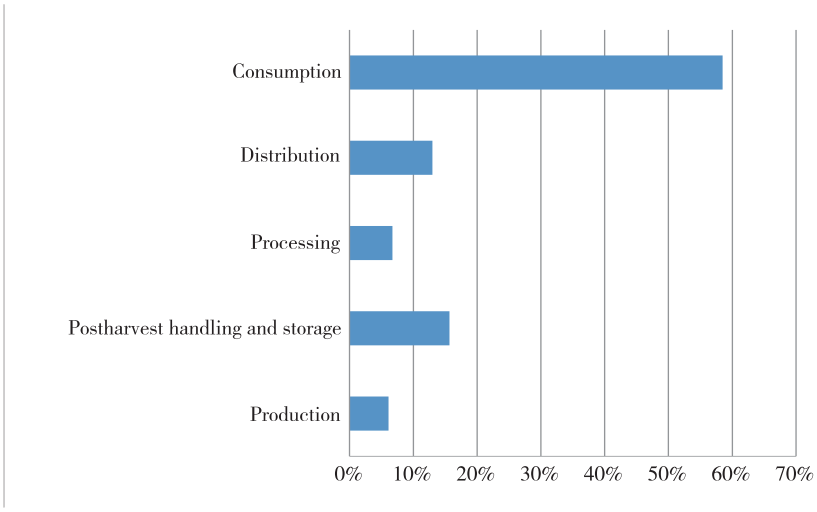
Further disaggregation analysis reveals that if there is a 50% FLW reduction across all stages of the food supply chain, the consumption stage alone contributes over half of the total mitigation (see Figure 6). With rapid urbanization and increasingly diversified dietary patterns, food waste at the consumption stage is becoming more prominent, particularly driven by trends in out-of-home dining and food preferences, which have normalized waste behaviors. This reinforces the need for targeted and comprehensive strategies at the consumer level.

In summary, while the consumption stage offers the highest carbon reduction potential, upstream interventions, particularly in postharvest handling and transportation, should not be overlooked. Advancing system-wide FLW reduction through public awareness campaigns, enhanced supply chain management systems, and optimized policy mechanisms will be important for accelerating progress toward China's peak carbon targets and carbon neutrality goals, as well as broader global sustainable development agenda.

Figure 5-5 Percentage change in carbon emissions relative to baseline for different levels of food loss and waste reduction

Scenarios		%	Low	%	Medium	%	High
S1	Production		−0.7		−1.7		−3.3
S2	Postharvest handling and storage		−1.8		−4.3		−8.4
S3	Processing	−10	−0.7	−25	−1.8	−50	−3.6
S4	Distribution		−1.4		−3.5		−7.0
S5	Consumption		−6.3		−15.7		−31.5

Figure 5-6 Contribution of different segments to carbon reduction under the halving of food loss and waste scenario



5.5 Food Loss and Waste Mitigation Strategies

5.5.1 International Strategies for Reducing Food Loss and Waste

Amid intensifying global food security pressures and tightening resource and environmental constraints, the international community has actively explored diverse governance pathways surrounding legal systems, technological applications, governance collaboration, and public guidance, leading to the formation of multifaceted strategies for FLW mitigation. Developed countries, leveraging robust institutional frameworks and technological advantages, have constructed governance models that involve multiple stakeholders across the entire supply chain, while emerging economies focus on institutional development and interest coordination, driving the gradual implementation of related policies. This study reviews representative practices in Europe, North America, and Asia, focusing on legal frameworks, technological innovations, and public participation.

(1) Legal Protection and Institutional Design: The Fundamental Support for Institutional Governance

Legal systems form the backbone of systematic FLW governance. Countries have introduced legislative guarantees, policy incentives, industry standards, and data regulation, to provide clear frameworks and pathways for FLW reduction actions.

1) Enhancing Legal Systems and Governance Frameworks

The United States has enacted landmark legislation since 1996, including the Bill Emerson Good Samaritan Food Donation Act, the Federal Food Donation Act (2008), the Food Recovery Act (2017), and the Food Date Labeling Act, among others. These laws clarify the boundaries of food donation responsibilities, standards for recovery, and operational guidelines for labeling (Shan, 2023). The European Union centered around the Waste Framework Directive (2008), has continuously promoted a shift in food waste legislation from end-of-life disposal to full-supply-chain prevention. The 2018 revision incorporated “food waste prevention” as a legal obligation, and the 2024 revision further included its environmental and climate impacts in legislative considerations. Complementary policies, such as the Food Donation Guidelines (2017) and the Feed Reuse Guidelines (2018), have been implemented to foster coordinated legislation on food donations, redistribution, and standardized labeling among member states, thus building a comprehensive regulatory framework for food loss reduction (Chen, 2022). Japan has developed a full-supply-chain regulatory framework that includes the Food Resource Recycling Promotion Act (2001), the Basic Act on Food Education (2005), the Food Recycling Act (2016), and the Food Waste Reduction Promotion Act (2019), strengthening monitoring from production to consumption. South Korea, through laws such as the Waste Management Act (1986-1992), the Food Reuse Act (2000), and the Organic Waste Biogasification Act (2022), has also implemented policies like “waste measurement and charging”, which increase public participation and corporate willingness to reduce waste (Lee et al., 2024).

2) Categorized Governance and Policy Implementation

To enhance practicality, many countries have adopted categorized governance and differentiated targets. The United States Environmental Protection Agency (EPA) has proposed a "Food Recovery Hierarchy" framework, which prioritizes actions such as source reduction, donation to hunger relief, feeding animals, industrial use, composting, and final disposal by landfill or incineration (Huang and Rao, 2021). EU member states, in accordance with unified regulations, have set national reduction targets. For example, France has banned large supermarkets from destroying unsold food since 2016, mandating that they sign donation agreements with food banks. Italy has simplified the donation process through legislation, clarified responsibilities at each stage, and incentivized businesses and farms through tax rebates. Japan, in its "Basic Plan for Promoting the Fourth Cycle-type Society" (2018), has committed to reducing food waste in households and businesses by 50% by 2030, compared to 2000 levels (Niu et al., 2022). To achieve this, the government has set recycling rate targets for key industries such as processing, retail, and catering and requires large enterprises to regularly report on waste generation and recycling, institutionalizing corporate governance responsibilities. Policy mechanisms are key to connecting policy goals with practical implementation. Common policy tools include fiscal incentives, such as Canada's "Food Infrastructure Fund", aimed at addressing food waste and improving access to food for vulnerable populations[1]. Compliance responsibility systems, such as Japan[2] and South Korea's[3] food donation registration and review mechanisms to foster a culture of food donation. Institutionalized processing mechanisms, such as Singapore's waste classification and reporting systems to standardize end-of-life disposal[4].

3) Data Support and Supervision Mechanisms

Effective governance requires accurate data and feedback loops. In 2019, the EU passed Delegated Decision 2019/1597, establishing a unified food waste measurement and reporting system, requiring member states to systematically monitor five major stages—production, processing, retail, catering, and households — every four years, using a combination of direct (e.g., waste composition analysis, mass balance method) and indirect (e.g., surveys, interviews, diary methods) approaches to ensure data comprehensiveness and comparability. In the United States, the non-profit organization ReFED, in cooperation with the Department of Agriculture and the EPA, has established a food loss database to promote national data collection and policy evaluation. Japan implements a system where companies report regularly, complemented by consumer affairs agency surveys, to collect data on food waste structure and trends at the household and corporate levels. South Korea uses standard garbage bags, stickers, or RFID (Radio Frequency Identification) electronic scales and app platforms to visualize, quantify, and dynamically regulate waste behavior, creating a precise and closed-loop digital governance system.

(2) Technological Transformation and Tool Application: Data-Driven Approaches and Efficiency Enhancement

The rapid development of digital and intelligent technologies has enabled several countries to pursue data-supported, traceable, and efficient FLW reduction strategies.

1) Smart Supply Chain Management and Loss Control

Food loss is concentrated in upstream and midstream stages. Technological optimization has become a key pathway for improving efficiency and reducing losses. Retail giants in the United States, such as Walmart and Unilever, apply big data analytics to understand consumer behavior, allowing them to adjust inventory and logistics arrangements in real-time, effectively reducing unsold waste and stockpile accumulation. In Japan, businesses combine information and communication technology (ICT) with artificial intelligence (AI) algorithms to precisely forecast order demands, dynamically optimizing cold-chain distribution paths, significantly reducing losses in the distribution phase. In Brazil, the National Agricultural Research Company (EMBRAPA) has developed modified atmosphere packaging (MAP) and edible antimicrobial coating technologies, which effectively extend the shelf

[1] https://www.mplongfield.ca/news/federal-government-renews-local-food-infrastructure-fund?

[2] https://www.jnpoc.ne.jp/en/insights/food-assistance-in-japan-current-state-of-japanese-food-banks/?

[3] https://www.foodbank1377.org/koreafoodbank/service.do?

[4] https://www.nea.gov.sg/our-services/waste-management/mandatory-waste-reporting?

life of fruits and vegetables. The startup "Caixa Verde" has adopted a "farm-to-consumer" model, bypassing wholesale channels to deliver surplus agricultural products directly from farmers to consumers, reducing circulation losses by 15% (Matzembacher, 2021). Germany and other countries also strongly promote intelligent temperature control and digital logistics systems, enhancing freshness and transport efficiency from the source (Shen et al., 2020).

2) Food Traceability and Redistribution Platform Development

Digital platforms enhance food redistribution efficiency. The largest food redistribution charity organization in the UK, "FareShare", has built a nationwide food redistribution network. It acquires high-quality surplus food from the food industry and supports more than 10,000 charitable and community organizations (Zhai, 2022). In South Korea, RFID waste bins with automatic weighing technology, combined with a point system and app feedback, guide residents to proactively reduce food waste. By 2021, the national separate collection rate for food waste had reached 88.8% (Lee et al., 2024). In Brazil, the "Invisible Food" platform uses blockchain technology to connect food service companies, supermarkets, and food banks, matching supply and demand in real-time. It uses geographic location and AI algorithms to push discounts on near-expiry food, encouraging "immediate consumption" at retail endpoints, significantly reducing end-point waste in pilot regions (Matzembacher, 2021).

3) Consumer Guidance Tools and Information Optimization Mechanisms

Misinterpreted labels cause household food waste. The U.S. Food and Drug Administration (FDA) introduced the "Food Date Labeling Act", which distinguishes between "Use By" (safe consumption date) and "Best If Used By" (optimal quality date), helping consumers accurately assess whether food is still safe to eat. The UK, Japan, and South Korea have also optimized labeling systems, promoting the redistribution and utilization of food within the best-before period, thereby enhancing food resource efficiency. Additionally, Japan has widely promoted "food bank" activities, where unsold food produced at various stages (production, circulation, retail) is donated to institutions in need. In South Korea, companies have developed an AI scanning system for "zero waste dishes", which records food waste in cafeterias and calculates the associated carbon emissions. Through visual feedback, the system encourages employees to select food more scientifically and reduce waste (Li et al., 2023).

4) Public Education Platforms and Feedback Systems

Raising public awareness is key. Many governments and non-governmental organizations enhance residents' food management capabilities through digital platforms. For instance, the U.S. Department of Agriculture and the Environmental Protection Agency jointly launched the "Food Waste Challenge" and the "Food Recovery Challenge" to mobilize participation from all sectors of society, raising awareness about food waste reduction and providing policy support. Japan emphasizes the promotion of "food education" (shokuiku) by engaging government, media, consumer organizations, and others to create a food-saving atmosphere. The Japanese Consumer Affairs Agency conducts annual special surveys to assess public awareness and the effectiveness of local policies, summarizing findings and providing feedback. In Brazil, the government, in collaboration with non-governmental organizations, initiated the "No Waste" challenge, encouraging households to share food-saving experiences and design environmentally friendly menus. This initiative reached over 5 million urban residents, significantly enhancing the spread and social influence of food-saving knowledge.

(3) Interdepartmental Collaboration and Public Participation: A Multidimensional Synergy in Governance Systems

Systemic FLW governance relies on coordinated action among governments, industries, NGOs, and citizens. Through the diverse collaboration of governments, businesses, social organizations, and the public, it helps facilitate the fundamental transformation from "localized interventions" to "systemic governance".

1) Interdepartmental Coordination Mechanisms and Multilevel Collaboration

Effective governance of FLW requires the establishment of robust interdepartmental coordination mechanisms and multilevel policy collaboration systems. Since 2018, the United States has launched the "Winning on Reducing Food Waste Initiative" through a joint effort by the Environmental Protection Agency (EPA), the

Department of Agriculture (USDA), and the Food and Drug Administration (FDA). This initiative promotes deep integration between local and national governments and various functional agencies through standardization, technological collaboration, public education, and data sharing. The European Union has set up the "EU Platform on Food Losses and Food Waste," bringing together multiple departments including agriculture, finance, and environment, in cooperation with the food industry, research institutions, and non-governmental organizations (NGOs). The platform regularly discusses policies and evaluates their effectiveness, establishing a systematized and multi-participant governance framework. Japan, led by the Cabinet, has established an interdepartmental liaison mechanism involving over 20 central ministries and agencies, forming a vertically and horizontally coordinated policy loop with clearly defined roles.

2) Corporate Responsibility and Industry Collaboration Platforms

Industry plays a pivotal role in FLW reduction strategies. The United Kingdom, under the guidance of the Waste and Resources Action Programme (WRAP), has implemented the "Courtauld Commitment", now in its fifth phase (Courtauld Commitment 2030), covering over 90% of food companies. This voluntary agreement sets clear loss reduction targets for companies and enhances responsibility through data disclosure, third-party evaluation, and performance tracking. In the United States, the "2030 Food Loss and Waste Champion Advocates" program recognizes companies that commit to halving FLW by 2030, providing positive industry incentives. Brazil, through collaboration between the government, industry associations, and research institutions, has established the "Food Waste Reduction Committee", promoting initiatives such as "Ugly Food Promotion Week" and "Non-standard Food Procurement Agreements". These practices combine corporate social responsibility with market innovation to integrate loss reduction and commercial value.

3) Mobilization of Non-Governmental Organizations and Charity Systems

Food banks are vital intermediaries. Non-governmental organizations, particularly food bank systems, play an increasingly critical role in global food waste governance. Acting as intermediaries between surplus food and social needs, food banks enhance the environmental sustainability of the food system while also strengthening the resilience and equity of social support systems. For instance, the Global Foodbanking Network distributed 654,000 tonnes of food to 40 million people worldwide in 2023, reducing CO_2 emissions by 1.8 million tonnes[5]. U.S.-based City Harvest[6], the UK's Felix Project[7], Germany's Foodsharing.de[8], and Japan's Second Harvest[9] have built efficient food recovery and distribution mechanisms, transforming surplus food from supermarkets, farms, and manufacturers into emergency aid supplies. This reduces landfill costs and supply chain losses, while serving vulnerable populations. Advanced practices in various countries further highlight the role of food banks in systemic governance. For example, Feeding America, the largest hunger relief organization in the U.S., has built collaborative networks across agriculture, manufacturing, and distribution sectors to facilitate the large-scale redistribution of surplus food. In Brazil, over 230 food banks have set up collection points in major public markets and coordinated with community kitchens and social organizations. By 2018, the average number of people served monthly reached 220,000 (Matzembacher et al., 2021). These practices demonstrate that food banks are not only an essential tool for loss reduction but also a key platform for enhancing the efficiency and resilience of food system governance.

4) Public Education and the Reshaping of Consumption Culture

Consumer behavior is a critical factor in food waste. Changing consumer habits is vital to achieving overall success. Japan has incorporated food waste reduction into the national education system through the Basic Food Education Law, establishing "Food Education Month" (June each year) and "Food Education Day" (the 19th of each month), combining health education with public knowledge dissemination and cultural shaping. Since 2007, the UK has launched the "Love Food, Hate Waste" platform under WRAP, creating a digital information delivery system. This platform provides customized menus, leftover handling advice, and storage optimization guides for households, using

[5] The Global Foodbanking Network. https://www.foodbanking.org/
[6] City Harvest. https://www.cityharvest.org/
[7] The Felix Project. https://thefelixproject.org
[8] Foodsharing.de https://foodsharing.de/
[9] Second Harvest. https://2hj.org

media, social platforms, online resource libraries, and offline workshops. It collaborates with local governments, women's associations, and schools to carry out public education, establishing a long-term mechanism for behavioral intervention and cultural transformation.

In summary, global FLW governance demonstrates considerable diversity and diverse pathways. Different countries have constructed governance frameworks tailored to their institutional foundations, resource endowments, and cultural identities (Table 2). Developed nations like the U.S., EU, and the UK, with established rule of law and social institutional maturity, have adopted governance models based on systematic policy tools, industry cooperation platforms, and public engagement mechanisms, driving the creation of a closed-loop governance system. Countries like Japan and South Korea, integrate cultural identity and educational systems, while emerging economies such as Brazil emphasize multi-stakeholder collaboration, integrating policy pilots, digital innovation, and public research platforms, forging a gradual governance pathway characterized by "multi-stakeholder collaboration". Food waste is not only a resource and environmental issue but also a comprehensive reflection of governance and social participation capacity. Achieving a transformative shift from "reduction" to "efficiency enhancement" and from "localized interventions" to "systemic restructuring", requires a robust framework of institutional design, technological support, and cultural alignment—advancing progress toward the UN SDGs and a more resilient global food system.

Table 5-2 Comparison of categorization and core characteristics of food waste governance models across countries

Country/Region	Pattern	Characteristics
US, EU, UK	Institutional-driven, Technological Co-governance	Comprehensive Regulatory Framework, Data Support, and Widespread Corporate Participation
Japan, Korea	Cultural-guided, Regulatory Integration	Food Education Leadership, Full-chain Coverage, and Strong Institutional Implementation Loop
Brazil	Collaborative Exploration, Platform-driven	Multi-stakeholder Interaction, Gradual Institutional Progression, and Emphasis on Technological Empowerment

5.5.2 Overview of China's Anti-Food Waste Policies and Measures

Since the founding of the People's Republic of China, the country's policies on food waste reduction have evolved from isolated initiatives to more comprehensive strategies. This progression spans from early awareness-raising efforts to institutionalized, rule-of-law-based mechanisms that encompass the entire food supply chain. This evolution can be divided into four distinct stages: 'Initial', 'Exploratory', 'Development', and 'Regulatory'. It began with the "Increase Production, Save Resources" movement, which focused on enhancing awareness of food conservation. Over time, the approach shifted towards guiding public behavior through campaigns, later evolving into a systemic governance framework targeting food waste across the entire supply chain. Ultimately, the legal system and multi-stakeholder collaboration were established to create a sustainable, long-term mechanism. This progression not only reflects the country's increasing emphasis on food security and resource conservation during different historical periods but also illustrates the inherent logic behind the transition of policies from conceptual advocacy to institutionalized, systematized, and rule-of-law-based frameworks. These stages reflect a shift from ideological advocacy to practical, coordinated governance, mirroring the country's growing emphasis on food security, resource efficiency, and sustainability

(1) Initial Stage: Raising Awareness of Food Conservation and Launching the Increase Production, Save Resources Movement (1949 - 1977)

In the early years of the People's Republic of China, it faced severe food shortages. In response, the government prioritized grain storage and preservation. For example, in 1950, the government issued the "Decision on the Unified Collection, Storage, and Dispatch of State Grain", which laid the groundwork for establishing national standards and technical measures for grain storage. In 1953, the Central Committee of the Communist Party of China (CPC) proposed the core idea of "strictly enforcing savings" in the "Resolution on Increasing Production, Raising Income, Practicing Strict Economy, Tightening Expenditure, and Balancing the National Budget", and initiated the nationwide "Increase Production, Save Resources" movement. That same year, in October, the CPC Central Committee issued the "Resolution on the Implementation of Planned Grain Procurement and Supply", which included measures to save grain by increasing purity and reducing precision in grain processing, as well as improvements in planned procurement and supply to reduce waste. From 1959 to 1961, natural disasters led to severe food shortages, exacerbating the hunger crisis (Zhou & Li, 2022). In 1962, the CPC again emphasized the necessity of food conservation in the "Decision on Grain Work" and called for the eradication of food spoilage, loss, and waste. In 1975, the State Council issued the "Directive on Further Advancing the Increase Production, Save Resources Movement", establishing the movement as a fundamental approach to developing the socialist economy and expanding socialist accumulation, and encouraging its institutionalization. These early policies and movements heightened public awareness of food conservation, fostered a culture of thrift, and laid a solid foundation for subsequent efforts to reduce food waste in China (Hu et al., 2024). These early efforts cultivated a culture of thrift and laid the groundwork for future food waste governance.

(2) Exploratory Stage: Promoting Multi-Form Food Conservation and Creating a Strong Awareness of Savings (1978 - 2007)

With reform and opening-up, China's food policies transitioned from a "supply-oriented" approach to a "savings-oriented" strategy. In 1979, the National Grain Conference reaffirmed the fundamental principles of "strictly enforcing savings and adhering to the conservation of grain", and the state introduced various policies promoting the reduction of food waste. Public campaigns promoted social norms such as e "wasting is shameful, conserving is honorable". Through recognizing achievements, criticizing waste, and guiding public opinion, the government successfully raised awareness of food conservation, deeply embedding the concept into the public psyche.

The 1987 State Council "Notice on the Current Grain Work," which emphasized curbing unreasonable consumption and preemptive purchases. The 1990 "Decision on Strengthening Grain Procurement and Sales" further called for public education on food-saving practices, advocating for "planned consumption and food saving" as well as the promotion of the idea that "wasting food is shameful, conserving food is honorable". The same year, the State Council's "Notice on Adjusting Grain Procurement and Sales Policies" underscored the importance of promoting the traditional virtues of thrift and scientific grain management to reduce losses and eliminate waste. In 1991, the State Council issued the "Notice on the National Grain Saving Week", designating the week of October 16th (World Food Day) as the "National Food Conservation and Saving Week," thus institutionalizing food conservation efforts and enhancing public awareness.

As part of its food conservation policies, in 2004, the Ministry of Agriculture and Rural Affairs (MARA) issued the "Notice on Implementing the Agricultural Machinery Technology for Grain Action Plan", aimed at promoting cost-reducing and efficiency-enhancing technologies in key crops like rice, wheat, corn, and soybeans to reduce food losses during production. In May 2006, the State Council released the "Opinions on Improving the Grain Circulation System", followed by the State Grain Administration's "Guiding Opinions on Grain Science and Technology Development During the 11th Five-Year Plan", both of which promoted new technologies to minimize grain losses and quality degradation risks during post-harvest and storage phases.

Through the combined implementation of these various food-saving policies, this phase embedded food conservation into public consciousness and laid the social and policy foundations for more systemic governance.. This environment not only provided a strong social foundation for the introduction of anti-food waste laws and regulations but also laid the groundwork for the future development of a governance mechanism involving multiple stakeholders working collaboratively.

(3) Development Phase: Formation of a Full-Chain Governance System and Inclusion of Catering Waste in Rectification Plans (2008 - 2020)

Triggered by the 2008 global financial crisis and food crisis, China reassessed its food security strategy. Facing dual pressures from external risk transmission and internal structural challenges, such as rising production costs, environmental degradation, and the rapid transformation of residents' dietary structures, the government began to emphasize food saving and loss reduction as integral to national food security.

With ongoing economic and social development, the issue of food waste reduction gradually became a major focus of national governance. The governance framework expanded, with policies extending from food production and storage to processing, circulation, and consumption. The goal of food saving and loss reduction also entered the "quantitative management" stage. However, this phase also faced numerous challenges, further driving the development of a full-chain reduction system and advancing the improvement of sustainable food systems.

In 2008, the National Development and Reform Commission (NDRC) released the "National Food Security Medium- and Long-Term Planning Outline (2008-2020)", which for the first time included "food saving and loss reduction" as an independent goal in the national food security strategy. The outline explicitly proposed "advocating for scientific food saving, improving food harvesting, storage, transportation, and processing methods, and reducing post-harvest food loss". The outline also added content related to public education, dietary structure, and catering consumption, calling for the guidance of scientific food saving practices, raising national food security awareness, and promoting a societal culture of cherishing food and opposing waste. Additionally, the outline set clear quantitative targets, requiring the food circulation loss rate to reduce from 8% in 2007 to 3% by 2020. Thus, China's food waste reduction policy entered a quantitative era, with catering waste explicitly included in the national plan, marking the shift of the food saving policy from emergency response to institutionalization.

In 2010, the General Office of the State Council issued the "Notice on Further Strengthening Food Saving and Opposing Waste", which provided detailed plans for various links in FLW. The notice emphasized the consolidation of responsibilities and collaborative efforts. It called for a focus on saving crops during sowing, field management, harvesting, and livestock breeding; improving grain storage conditions to enhance food quality; promoting new technologies in food processing to prevent unreasonable food conversion; developing new transportation equipment and improving the food collection and distribution network to reduce losses in food transportation; and promoting food-saving measures in catering, particularly in cafeterias. These policy deployments across multiple sectors marked the formation of a full-chain food saving and loss reduction policy system.

In December 2012, the Political Bureau of the Central Committee of the Communist Party of China (CPC) reviewed and approved the "Eight Provisions", which made clear regulations regarding thrift and frugality. In January 2013, General Secretary Xi Jinping issued an important directive, emphasizing the need for strict frugality and opposition to waste[10]. In 2014, the General Office of the CPC Central Committee and the State Council jointly issued the "Opinions on Strengthening Thrift and Opposing Food Waste", reiterating the importance of combating catering waste, and supplementing policy suggestions for full-chain reduction. In December of the same year, the State Council issued the "Opinions on Establishing and Improving the Food Security Provincial Governor Responsibility System", which incorporated "actively promoting food saving and loss reduction, guiding urban and rural residents toward healthy consumption" as a performance indicator for provincial-level food security work, clearly defining local governments' responsibilities in food waste reduction actions and establishing a governance mechanism of "horizontal coordination and vertical linkage" between central and local authorities. In 2016, the NDRC and the National Grain Bureau issued the "13th Five-Year Development Plan for the Grain Industry", which proposed "accelerating the formation of a government-led, enterprise-implemented, public-participating, and joint-action mechanism for grain saving and loss reduction, and reducing losses at all links of the food circulation chain", marking a comprehensive upgrade of the food saving and loss reduction mechanism.

In early 2020, the outbreak of the COVID-19 pandemic not only posed a significant threat to public health but also greatly increased the risk of

[10] http://theory.people.com.cn/n/2013/0201/c40555-20398076.html

macroeconomic downturn. Due to the infectious nature of the virus, the food industry suffered severely, with the food supply and demand system experiencing localized information imbalances and severe resource waste.

President Xi Jinping issued an important directive emphasizing the urgency of combating food waste. Since then, various departments have promoted the establishment of a frugal and food-saving culture across the entire society, advocating for the "clean plate" campaign. In 2020, the National Food and Strategic Reserves Administration issued a "Notice on Innovating Measures and Increasing Efforts to Further Strengthen Food Saving and Loss Reduction", outlining systematic deployments across legislative amendments, system construction, technological innovation, and public guidance, and clarifying the establishment of a working pattern of "government leadership, demand-driven, public participation, and social coordination", pushing food saving and loss reduction from policy advocacy to institutional governance and from single-point promotion to system-wide collaboration. In September of the same year, the Ministry of Education issued a notice on the "Action Plan to Curb Catering Waste and Cultivate Saving Habits in the Education System", marking an important step in the education system's efforts to reduce food waste. These efforts formalized the shift from reactive to institutional food waste governance.

In terms of specific policy measures, various sectors have formulated a series of specialized plans to achieve food saving and loss reduction targets:

● Production Link: The "Science and Technology to Revitalize Grain Project" was vigorously promoted, and the transformation and upgrading of agricultural mechanization was accelerated. In 2015, the "Notice on Strengthening the Quality of Grain Harvesting Operations" proposed reducing field losses by training agricultural machine operators and enhancing machinery supervision.

● Storage Link: The former National Grain Bureau launched a special project for scientific grain storage among farmers, promoting the use of new grain storage equipment through financial subsidies and improving the rural grain storage environment. The "Twelfth Five-Year Plan for Scientific Grain Storage Among Farmers" and "Management Measures for the Special Project of Scientific Grain Storage Among Farmers" issued in 2011 clarified the scope of funds and evaluation mechanisms, facilitating policy implementation.

● Transportation Link: The national level strengthened the construction of food logistics infrastructure to improve transportation efficiency and reduce spillage and spoilage. In 2014, the National Grain Bureau issued the "Notice on Promoting Grain Saving and Loss Reduction and Opposing Food Waste", proposing the strengthening of grain loading and unloading management and supervision during transportation.

● Processing Link: The National Grain Bureau and other relevant departments issued the "Notice on Promoting Grain and Oil Processing Industry Food Saving and Loss Reduction" (2014), guiding and standardizing enterprises to engage in moderate processing, resolving excess initial processing capacity, and promoting the comprehensive utilization of grain resources in the processing link.

● Consumption Link: A series of notices have been issued, including the "Notice on Saving Grain and Opposing Food Waste in Central and State Organs" (2008), the "Regulations on Strictly Enforcing Thrift and Opposing Waste in Party and Government Organs" (2013), and the "Opinions on Promoting Thrift and Opposing Food Waste" (2014), which provide systematic requirements for public catering management, catering industry standards, control across the entire food chain, resource utilization, and public education and legal supervision, forming a guidance mechanism from policy advocacy to behavioral norms.

(4) Regulatory Phase: Food Waste Reduction Elevated to Legal Status, Multi-Stakeholder Participation Forms Social Synergy (2021-Present)

Since the initiation of the "Food Conservation Campaign" in 2021, the Central No. 1 Document has consecutively highlighted FLW reduction as a crucial task for agricultural and rural development, making it an important part of "the Three Rural Issues" (agriculture, rural areas, and farmers) for five consecutive years. The policy's scope has progressively expanded from the consumption stage to the entire supply chain, with the focus gradually shifting from public awareness to the construction of mechanisms and the rule of law. The 2021 enactment of the "Anti-Food Waste Law of the People's Republic of China" marked a pivotal turning point. For the first time, food conservation became a legal obligation, clearly defining responsibilities across government, industry, and society, and introducing legal accountability and incentive mechanisms. This law clearly defines food waste, governance principles, and basic requirements, delineates the responsibilities of government departments and various societal stakeholders, and establishes incentive and accountability mechanisms with legal provisions. That same year, multiple government bodies, including the General Office of the CPC Central Committee, the General Office of the State Council, and the National Development and Reform Commission (NDRC), issued a series of policy documents such as the "Full-Chain Food Conservation and Waste Reduction Action Plan", "Food Conservation Action Plan", and "Anti-Food Waste Action Plan". These documents comprehensively cover all stages of food production, from farm to table, including production, post-harvest drying and storage, multi-modal transportation of bulk grain, processing and transformation, and food consumption in catering services. The policy framework also constructs a collaborative long-term governance mechanism involving standards formulation, monitoring and evaluation, legal regulation, and social mobilization. This organic connection between policy guidance and institutional constraints provides solid support for national food security and high-quality development.

In 2023, the "Food Security Guarantee Law of the People's Republic of China" further institutionalized food waste governance by introducing a dedicated chapter on "Food Conservation", reinforcing the legal backbone of national food security policy. In 2024, the General Office of the CPC Central Committee and the General Office of the State Council jointly issued the "Food Conservation and Anti-Food Waste Action Plan", once again emphasizing the importance of combating food waste as a key strategy for ensuring food security, pushing food waste reduction to deeper levels, and further refining policy implementation pathways and governance priorities.

To strengthen technical support and institutional integration, the State Council and relevant ministries have continuously introduced targeted policy tools. In 2021, the Ministry of Agriculture and Rural Affairs issued a notice to include loss control during harvesting as a key task within the mechanization quality assessment system, encouraging the upgrading of agricultural machinery and standardizing operational procedures. In the same year, the National Food and Strategic Reserves Administration published the "Government Grain Storage Management Regulations", establishing a management system covering the entire food storage process. In 2022, the Ministry issued the "Notice on the Key Points for Building High-Standard Grain Warehouses (Trial)", setting specific technical standards for storage facilities, including warehouse structure, temperature and humidity control, and green energy efficiency, driving the green and intelligent transformation of the grain storage sector. The 2023 revision of the "Grain Quality Safety Supervision Regulations" further refined the monitoring of storage quality, the inspection of inbound and outbound grain, and the mechanism for handling problematic grains, enhancing synergy between food safety and conservation objectives.

In recent years, President Xi Jinping has made several important statements regarding the issue of food waste, emphasizing that "stopping food waste in catering is a long-term task that must be relentlessly pursued to build a conservation-oriented society"[11]. This significant assertion provides guidance for China's efforts to build a conservation-oriented society. Various levels of government have quickly responded and taken proactive action, continuously advancing institutional development and practical implementation. Especially in the field of catering waste management, the policy system has been continuously improved. In June 2023, the State Administration for Market Regulation and the Ministry of Commerce jointly issued the "Guiding Opinions on Leveraging Online Food Delivery Platforms to Lead and Effectively Prevent Food Waste in Takeaway Food". In March 2024, the Ministry of Commerce and nine other departments jointly issued the "Guiding Opinions on Promoting the High-Quality Development of the Catering Industry". In April and November of the same year, the State Administration for Market Regulation released notices on continuing to regulate marketing practices to prevent food waste by food delivery businesses. These policy documents provide specific guidance for the food service sector on food waste reduction across various areas, including market supervision, packaging materials, and recycling efforts. They strengthen industry standards and promote the formation of a green, low-carbon

[11] https://www.news.cn/politics/leaders/2022-06/24/c_1128773040.htm

catering consumption model. These measures promote green consumption models and prevent over-marketing and portion inflation.

With the implementation of the "Anti-Food Waste Law", food waste governance has officially entered a legal framework. Following the policy rollout, various stakeholders, from higher-level governments to businesses and the general public, have actively responded and collaborated, gradually forming a powerful collective effort to reduce FLW. Both central and local governments have strengthened policy implementation and regulatory innovation, businesses have optimized operating models and fulfilled social responsibilities, and the public has actively participated in food conservation practices such as the "Clean Plate Campaign". This has led to the formation of a multi-level, integrated governance system characterized by "government leadership, corporate responsibility, social collaboration, and public participation". This series of systemic reforms not only provides strong support for the implementation of national food security strategies but also injects robust momentum into high-quality economic and social development, fully demonstrating China's unique wisdom and institutional advantages in food loss reduction governance.

This integrated approach reflects a mature transition from piecemeal efforts to a comprehensive governance regime, reinforcing China's commitment to food security, sustainable development, and high-quality growth.

5.6 Pathways for Reducing Food Loss and Waste in China

As the world's most populous nation and a major agricultural producer, China's food system encompasses a comprehensive and complex supply chain, spanning from farm to table. In recent years, FLW issue has become increasingly prominent, exhibiting clear temporal, structural, and regional differences. The causes of FLW vary, necessitating differentiated reduction strategies and tailored policy interventions. Compared to production and distribution stages, reducing food waste at the consumption stage has a more significant carbon emission reduction effect. These interventions are primarily driven by behavior change, requiring minimal capital and infrastructure investment. Not only do they directly reduce food waste and its embedded carbon emissions, but they also avoid additional emissions associated with more resource-intensive mitigation measures.

By contrast, reducing food loss in upstream stages often necessitates sustained investments in capital, technology, and infrastructure, which may, to some extent, create new carbon emission pressures. Therefore, consumption-stage interventions are key to achieving efficient and low-cost carbon emission reductions. More importantly, reducing food waste enhances resource utilization efficiency, improves national nutrition and health levels, and contributes to broader social and ecological civilization.

To address these challenges holistically, a systematic approach is required, focusing on three dimensions: supply chain collaboration, consumption-end interventions, and policy-level safeguards. This approach should promote multi-stakeholder collaboration, integrate diverse strategies, and explore the development of a coordinated reduction pathway and governance system with Chinese characteristics.

(1) Supply Chain Collaboration: Enhancing Loss Reduction Capacity Across the Entire Chain

FLW in China's food system is mainly concentrated in the production, post-harvest and storage, processing, and distribution stages, especially with perishable items such as fruits, vegetables, and aquatic products, which are highly vulnerable due to inadequate cold chain infrastructure. Current loss reduction measures are fragmented in technology, disconnected in system integration, and characterized by information silos, making it difficult to achieve efficient collaboration across the entire supply chain. A systemic optimization is urgently needed.

First, accelerate the development of post-harvest cold chain systems and standardize logistics. In particular, establish "low-loss agricultural product distribution centers" in major production areas, integrating post-harvest precooling, grading, packaging, modified atmosphere preservation, smart storage, and green cold chain transportation to promote the integration and demonstration of loss reduction technologies.

Second, leverage platforms such as the Internet of Things (IoT) and big data to enhance connectivity between production and sales, streamline inventory management and logistics, and establish a robust, data-driven supply chain to improve operational efficiency and reduce spoilage and backlogs.

Third, Promote national and industry-specific loss reduction standards, particularly for post-harvest handling, cold chain logistics, storage and distribution, to standardize technical practices and ensure consistent implementation.

Fourth, strengthen investment in cold chain infrastructure in central, western, and remote regions, improving urban-rural cold chain integration and enhancing national supply chain resilience..

Last, promote the use of green and low-carbon technologies in new infrastructure to minimize emissions and align food loss reduction with sustainability and climate goals.

(2) Consumption-Stage Interventions: Guiding Public Behavior Change

In China, food waste at the consumption stage is primarily concentrated in the catering services sector, particularly in banquets, where social norms such as "face culture" lead to over-ordering. The value of frugal consumption is not yet fully internalized as a societal norm, and a gap remains between institutional constraints and cultural guidance. FLW issues in households, supermarkets, and food delivery services also require attention and systematic intervention. In response, the following measures should be prioritized:

First, the construction of consumption scenes that promote saving should be strengthened. The "Guidelines for Saving-Oriented Catering Services" should be implemented, advocating for smaller portion sizes, family-style meals, the use of public serving utensils, and smart ordering reminders. Supermarkets and food delivery platforms should also adopt portion-based supply, custom orders, and food packaging for leftovers to promote rational consumption.

Second, a food waste data feedback mechanism should be established. The promotion of "leftover food public display" and "carbon footprint labels" will increase consumer awareness of the environmental impact of waste, stimulating awareness of food-saving and environmental protection.

Third, a systematic food-saving education framework should be developed. FLW education should be incorporated into primary and secondary school curricula and general education in universities, complemented by activities such as "Clean Plate Campaigns" and "Food Saving Challenges" to foster a culture of saving. Fourth, local legislation and incentive mechanisms should be refined. Measures such as reward points, waste penalties, and civilized dining assessments should be explored to form a dual-driven regulatory path combining advocacy and institutional measures. In addition, the application of digital technologies in household and restaurant management, such as ingredient management apps and smart refrigerators, should be promoted to improve food management efficiency and reduce household waste, achieving both reduction and carbon reduction benefits.

(3) Policy-Level Safeguards: Improving Legal and Incentive Systems

While China has made significant progress through the "Anti-Food Waste Law" and the "Food Saving and Anti-Food Waste Action Plan", challenges remain at the implementation level, such as fragmentation of responsibilities, regulatory inefficiency, and unclear accountability, leading to insufficient governance coordination and limited effectiveness. Therefore, the following improvements should be made:

First, cross-departmental collaborative governance should be promoted. A national food loss reduction coordination mechanism should be established, led by the MARA and involving multiple departments. This mechanism should strengthen data sharing, joint enforcement, and task coordination, breaking down administrative silos. At the same time, FLW reduction targets should be incorporated into China's Nationally Determined Contributions (NDC), with clear quantitative indicators (e.g., reducing FLW in the supply chain and consumption end by 50% by 2030) aligned with carbon peak and carbon neutrality strategies to enhance policy coherence.

Second, legal protections and incentive support should be refined. Further clarify responsibilities under the "Anti-Food Waste Law" and embed FLW reduction into broader national strategies such as food security and carbon peak targets. Special funds and green financial tools should be set up to support technological innovation and local pilot programs, attracting social capital participation.

Third, a unified monitoring and evaluation system should be established. Develop a unified "Food Loss and Waste Monitoring and Evaluation Method" and institutionalize an annual "Food Loss Reduction Report System", to improve transparency, assess progress, and support evidence-based policymaking.

Fourth, local legislation and standards innovation should be promoted. Encourage major food-producing regions and large cities to pilot legislation and develop local standards, exploring a governance model based on central coordination, local innovation, and upward-downward integration.

Fifth, South-South cooperation should be strengthened to share China's experience. Promote international collaboration by sharing China's experiences in legislation, technological solutions, capacity building, and pilot projects to help developing countries establish context-appropriate FLW reduction systems.

China's FLW governance is at a critical transition from policy-driven to mechanism-driven approaches, and from awareness -based advocacy to systemic governance. It is essential to strengthen the coordination of policies and technologies, as well as the parallel development of consumption concepts and institutional constraints, to foster synergy between public awareness and regulatory enforcement. Through a full-chain closed-loop management system and multi-stakeholder collaboration, China can develop a comprehensive and characteristic pathway for FLW reduction. This not only safeguards national food security but also accelerates the green, low-carbon sustainable transformation of agrifood system.

Reference:

Alexander, P., C. Brown, A. Arneth, J. Finnigan, D. Moran, and M.D.A. Rounsevell. 2017. Losses, inefficiencies and waste in the global food system. Agricultural Systems 153: 190-200.

Al-Khateeb, S.A., A. Hussain, S. Lange, M.M. Almutari, and F. Schneider. 2021. Battling food losses and waste in saudi arabia: Mobilizing regional efforts and blending indigenous knowledge to address global food security challenges. Sustainability 13(15): 1-19.

Benyam, A. A., Soma, T., and Fraser, E. 2021. Digital agricultural technologies for food loss and waste prevention and reduction: Global trends, adoption opportunities and barriers. Journal of Cleaner Production 323: 129099.

Bräutigam K R, Jörissen J, Priefer C. The extent of food waste generation across EU-27: Different calculation methods and the reliability of their results. Waste Management & Research, 2014, 32(8): 683-694.

Brennan, L., S. Langley, K. Verghese, S. Lockrey, M. Ryder, C. Francis, N.T. Phan-le, and A. Hill. 2021. The role of packaging in fighting food waste: A systematised review of consumer perceptions of packaging. Journal of Cleaner Production 281: 125276.

Ciccullo, F., R. Cagliano, G. Bartezzaghi, and A. Perego. 2021. Implementing the circular economy paradigm in the agri-food supply chain: The role of food waste prevention technologies. Resources, Conservation & Recycling 164: 105114.

Elik, A., D.K. Yanik, Y. Istanbullu, N.A. Guzelsoy, A. Yavuz, and F. Gogus. 2019. Strategies to Reduce Post-Harvest Losses for Fruits and Vegetables. Strategies to Reduce Post-Harvest Losses for Fruits and Vegetables 5(3): 29-39.

European Commission. 2020. A Farm to Fork Strategy for a Fair, Healthy and Environmentally-friendly Food System.

European Commission. 2020. Circular Economy Action Plan: For a Cleaner and More Competitive Europe.

FAO. 2019. The State of Food and Agriculture 2019. Moving forward on food loss and waste reduction. Rome, Italy.

FAO, IFAD, UNICEF, WFP, and WHO. 2024. The State of Food Security and Nutrition in the World 2024: Financing to End Hunger, Food Insecurity and Malnutrition in All Its Forms. Rome: FAO. https://doi.org/10.4060/cd1254en

Food and Agriculture Organization of the United Nations 2013. Food Wastage Footprint: Impacts on Natural Resources: Summary Report. Rome. http://www.fao.org/3/i3347e/i3347e.pdf.

Geyik, Ö., M. Hadjikakou, and B.A. Bryan. 2022. Climate-friendly and nutrition-sensitive interventions can close the global dietary nutrient gap while reducing GHG emissions. Nature Food 4(1): 61-73.

Gustavsson J, Cederberg C, Sonesson U, et al. 2011. Global food losses and food waste. Rome: FAO.

Harvey, J., A. Smith, J. Goulding, and I. Branco. 2020. Food sharing, redistribution, and waste reduction via mobile applications: A social network analysis. Industrial Marketing Management 88: 437-448.

Jiang, S., H. Chen, S. Yang, Y. Wang, and M. Xu. 2023. Assessment and scenario hypothesis of food waste in China based on material flow analysis. Npj Urban Sustainability 3(1): 1-9.

Lee, E., Shurson, G., Oh, S. H., Jang, J. C. 2024. The management of food waste recycling for a sustainable future: A case study on South Korea. Sustainability,

16 (2), 854.
Lesk, C., P. Rowhani, and N. Ramankutty. 2016. Influence of extreme weather disasters on global crop production. Nature 529(7584): 84-87.
Liu, C., Y. Hotta, A. Santo, M. Hengesbaugh, A. Watabe, Y. Totoki, D. Allen, and M. Bengtsson. 2016. Food waste in Japan: Trends, current practices and key challenges. Journal of Cleaner Production 133: 557-564.
Li, Y., L. en Wang, G. Liu, and S. Cheng. 2021. Rural household food waste characteristics and driving factors in China. Resources, Conservation and Recycling 164: 105209.
Li, Z., P. Sui, X. Yang, H. Dai, X. Wang, P. Long, L. Yan, and Y. Chen. 2017. Balancing GHG mitigation and food security through agricultural recycling systems: Case studies in the North China Plain. Journal of Cleaner Production 157: 222-231.
Lu, S., G. Cheng, T. Li, L. Xue, X. Liu, J. Huang, and G. Liu. 2022. Quantifying supply chain food loss in China with primary data: A large-scale, field-survey based analysis for staple food, vegetables, and fruits. Resources, Conservation and Recycling 177: 106006.
Matzembacher D E, Vieira L M, de Barcellos M D. 2021. An analysis of multi-stakeholder initiatives to reduce food loss and waste in an emerging country-Brazil. Industrial Marketing Management, 93: 591-604.
Niu, Z., S.J. Ng, B. Li, J. Han, X. Wu, and Y. Huang. 2022. Food waste and its embedded resources loss: A provincial level analysis of China. Science of the Total Environment 823: 153665.
Ogunmoroti, A., M. Liu, M. Li, and W. Liu. 2022. Unraveling the environmental impact of current and future food waste and its management in Chinese provinces. Resources, Environment and Sustainability 9(May): 100064.
Read, Q.D. and M.K. Muth. 2021. Cost-effectiveness of four food waste interventions: Is food waste reduction a "win-win?" Resources, Conservation & Recycling 168: 105448.
Ren, M., C. Huang, Y. Wu, A. Deppermann, S. Frank, P., et al. 2023. Enhanced food system efficiency is the key to China's 2060 carbon neutrality target. Nature Food 4(7): 552-564.
Reynolds, C., L. Goucher, T. Quested, S. Bromley, S. Gillick, V.K. Wells, D. Evans, et al. 2019. Review: Consumption-stage food waste reduction interventions-What works and how to design better interventions. Food Policy 83: 7-27.
Romanazzi, G. and M. Moumni. 2022. Chitosan and other edible coatings to extend shelf life, manage postharvest decay, and reduce loss and waste of fresh fruits and vegetables. Current Opinion in Biotechnology 78: 102834.
Soma, T., B. Li, and V. Maclaren. 2020. Food Waste Reduction: A Test of Three Consumer Awareness Interventions. Sustainability 12: 907.
UN. 2015. Sustainable Development Goals 2030. https://sustainabledevelopment.un.org.
United Nations Environment Programme. 2021. Food Waste Index Report 2021. Nairobi.
World Bank. 2020. Addressing Food Loss and Waste: A Global Problem with Local Solutions. Washington, D.C. http://hdl.handle.net/10986/34521.
Xue L, Liu X, Lu S, et al. 2021. China's food loss and waste embodies increasing environmental impacts. Nature Food, 2(7): 519-528.
Zamri, G. B., Azizal, N. K. A., Nakamura, S., Okada, K., Nordin, N. H., Othman, N., Sobian, A., Kaida, N. and Hara, H. 2020. Delivery, impact and approach of household food waste reduction campaigns. Journal of Cleaner Production 246: 118969.
Zhang H, Liu G, Xue L, et al. 2020. Anaerobic digestion based waste-to-energy technologies can halve the climate impact of China's fast-growing food waste by 2040. Journal of Cleaner Production, 277: 123490.
Zhu J, Luo Z, Sun T, et al. 2023. Cradle-to-grave emissions from food loss and waste represent half of total greenhouse gas emissions from food systems. Nature Food, 4(3): 247-256.
Cao F, and Wu L. 2024. The impact of reducing losses and waste at the whole supply chain food security in China: simulation analysis based on the partial equilibrium model. Journal of Agrotechnical Economics, (05): 76-90.
Chen C. 2022. The practical experience of EU action against food waste and China's enlightenment. World Agriculture, (12): 24-33.
Cheng S, Gao L, Xu Z, Tang C, Wang L, and Dhruba Bijaya G.C. 2012. Food waste in catering industry and its impacts on resources and environment in China. China Soft Science, (07): 106-114.
Hu Y, Hu N, Zhang K, and Wu L. 2024. Grain saving and loss reduction policies in China: evolution, logic, and optimization. Issues in Agricultural Economy, (10): 120-133.
Hu Y, Hu N, and Wu L. 2024. Assessment of the resource and environmental effects of China's grain loss and waste in 2022. Journal of Arid Land Resources and Environment, 38(09): 12-19.
Huang X, and Rao N. 2021. Foreign investigation of food conservation legislation and its reference. Journal of Chongqing University(Social Science Edition), 27(04): 101-114.
Jiang J, T.E. Yu, Huang W, and Wang Z. 2018. Home food

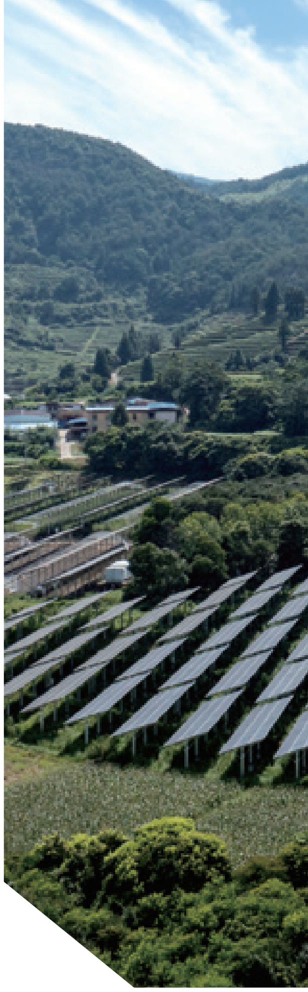
waste in China and the associated determinants. Journal of Agrotechnical Economics, (09): 88-99.
Li F, Ding Y, and Cai R. 2021. The degree and influencing factors of household food waste in China from the perspective of food conversion: An empirical analysis based on CHNS database. Journal of Natural Resources, 36(04): 811-826.
Li T. 2023. International experience in the management to reduce food loss and waste and its enlightenment to China. Science and Technology of Cereals Oils and Foods, 31(05): 208-216.
Long X, Wang L, Wan Q, Yang C, and Zhao X. 2025. Measurement of beef cattle industry chain losses and analysis of loss reduction paths. Chinese Journal of Agricultural Resources and Regional Planning, 46(03): 71-81.
Lu S, Liu X, Xue L, Tang Z, Liu G, and Cheng G. 2019. Addressing the losses and waste of Chinese rice supply chain: sources, drivers and mitigation strategies. Scientia Agricultura Sinica, 52(18): 3134-3144.
Luo Y, Li X, Huang D, and Wu L. 2020. The progress and prospects of research on food loss and waste. Journal of Natural Resources, 35(05): 1030-1042.
Niu K, Shen Y, Liu J, and Song R. 2022. Anti-food loss and waste: Japanese experience and insights. Journal of Natural Resources, 37(10): 119-129.
Shen Y, Niu K, Song R, Liu J, Zhu T, and Weng L. 2023. The implement of anti-food waste policy: international experience and local practice. Chinese Journal of Agricultural Resources and Regional Planning, 44(01): 119-129.
Shen L. 2020. Strategic action against food waste in Germany. World Agriculture, (10): 124-126.
Wang L, Ni X, Li Y, and Cheng S. 2021. Measurement of the scale of food waste and its resources and environmental effects at the consumer segment in China. Journal of Natural Resources, 36(06): 1455-1468.
Wang X, Tan X, and Zhou L. 2021. Subtracting well: the current situation and prospects of research on food saving and loss reduction. World Agriculture, (11): 4-11+118.
Wu L. 2022. Grain loss and waste in China: current situation, reduction potential and counter-measures. Issues in Agricultural Economy, (11): 34-41.
Zhai H. 2022. British anti-food-waste mechanism and its enlightenment to China. Journal of Qingdao Agricultural University(Social Science), 34(04): 74-80+99.
Zhang P, Sun F, Zhang D, and Wang L. 2024. Urban household food waste behavior and reduction strategies in China: A case study of Zhengzhou city. Journal of Natural Resources, 39(10): 2418-2430.
Zhou G, and Li S. 2022. Evolution and conceptualization of the policy expression “food for thought”. China Grain Economy, (02): 15-18.
Zhu Q, Li F, and Qian Z. 2020. A survey of canteen food waste and its carbon footprint in universities national wide. Journal of Arid Land Resources and Environment, 34(01): 49-55.

Chapter 6

Low-carbon Transformation of China's Agrifood Systems Through a Multi-Pronged Approach

Yumei Zhang[1,2], Li Chai[1,3], Yuquan Chen[1,2], Tiantian Sun[1,2], Junqing Song[1,2], Shenggen Fan[1,2], Ying Qiu[4], and Fang Sun [4]

1. Academy of Global Food Economics and Policy (AGFEP), China Agricultural University
2. College of Economics and Management, China Agricultural University
3. International College of Beijing, China Agricultural University
4. Environmental Defense Fund (EDF) Beijing Representative Office



Key Findings

● China's agrifood system is a major source of greenhouse gas (GHG) emissions, particularly methane (CH_4) and nitrous oxide (N_2O). In 2021, it emitted nearly 1.6 billion tonnes of CO_2eq, up from 1.2 billion tonnes in 2005, accounting for 12% of the country's total emissions. That year, agricultural activities contributed 40% of China's methane emissions (24.3 million tonnes, or 680 million tonnes of CO_2eq) and 45% of nitrous oxide emissions (0.9 million tonnes, or 250 million tonnes of CO_2eq). Without strong mitigation, agrifood system emissions could exceed 1.8 billion tonnes of CO_2eq by 2060, driven by rising energy consumption and livestock-related emissions.

● Carbon sinks from land use, land-use change, and forestry (LULUCF) in China increased substantially, reaching 1.3 billion tonnes of CO_2eq in 2021. Key contributors include afforestation, improved farmland management and grassland protection. Even under a conservative scenario—assuming only continued growth in forest carbon sequestration, LULUCF sinks could reach near 1.8 billion tonnes of CO_2eq by 2060.

● Reducing agrifood system emissions requires a multi-pronged strategy. Effective mitigation must combine with productivity improvements, low-carbon technologies, reductions in food loss and waste, dietary shifts, and clean energy adoption. With integrated mitigation and carbon sequestration, China can achieve the goals of both increased food production and lower emissions. Agrifood system emissions could fall by over 60% by 2060 to 650 million tonnes of CO_2eq, which can be fully offset by LULUCF carbon sinks. This would result in a net carbon sequestration of 1.1 billion tonnes of CO_2eq, which can contribute to the achievement of national carbon neutrality.

Policy Recommendations

● First, a strategic roadmap for low-carbon transformation of agrifood systems should be developed, incorporating a comprehensive strategy and phased action plan for emissions reduction and carbon sequestration. Robust scientific monitoring and evaluation frameworks must be established to provide the necessary support. Low-carbon objectives should be mainstreamed into existing agricultural and rural development policies to ensure an integrated and sustained transformation.

● Second, a multi-pronged approach is important for reducing carbon emissions. Investment in low-carbon agricultural technologies that enhance productivity should be significantly scaled up. Food production and consumption patterns must align with both nutritional and climate goals by prioritizing healthy, low-emission diets. Reducing food loss and waste across the entire supply chain is also critical. The adoption of clean energy should be expanded, and energy efficiency improved across all stages of the agrifood value chain.

● Third, carbon sequestration should be promoted through market-based incentives. Increased support should be directed toward research and development, particularly for localized ecological carbon sequestration technologies that integrate conservation with climate goals. Carbon markets and green finance systems should be strengthened by incorporating LULUCF carbon sinks into voluntary carbon credit mechanisms. Innovative green financial products linked to farmland protection, afforestation, and grassland restoration should be developed, transforming carbon sequestration into tangible economic value and creating a win-win outcome for climate action and rural livelihoods.

6.1 Introduction

As the climate change intensifies, achieving global temperature targets has become increasingly difficult, underscoring the urgency of emission reductions. As a major contributor to greenhouse gas (GHG) emissions, agrifood systems are central to mitigation efforts. Driven by population growth and rising demand for animal-based foods, emissions from agrifood systems continue to increase, exacerbating the challenge. Research shows that if current emission trajectories persist, even a complete halt in fossil fuel use would be insufficient to limit the 1.5°C or 2°C global temperature targets (Clark et al., 2020).

In response to this urgency, the international community has prioritized emission reductions in agrifood systems. The Food and Agriculture Organization (FAO) has developed the *Global Roadmap for Achieving Sustainable Development Goal 2 (SDG2) without Breaching the 1.5°C Threshold,* which aims to reduce GHG emissions from agrifood systems by 25% between 2020 levels and 2030, achieve carbon neutrality by 2035, and transform agrifood systems into a net carbon sink by 2050 (FAO, 2023).

China has also made climate commitments, pledging to peak carbon emissions by 2030 and reach carbon neutrality by 2060. To support these goals, the Ministry of Agriculture and Rural Affairs (MARA), alongside the National Development and Reform Commission (NDRC), launched the *Implementation Plan for Agricultural and Rural Emission Reduction and Carbon Sequestration* and introduced *Ten Major Technological Models for Agricultural and Rural Emissions Reduction and Carbon Sequestration*. In November 2023, the Ministry of Ecology and Environment, along with other agencies, issued the *Methane Emission Control Action Plan*, which outlines mitigation strategies through resource utilization in rice fields, livestock and poultry waste management, and improved control of methane from enteric fermentation.

While China's agriculture has seen rapid growth in recent decades, with substantial increases in output, its high-input, high-output production model has driven up GHG emissions. In 2021, methane and nitrous oxide emissions from agricultural activities reached 680 million and 250 million tonnes of CO_2eq, respectively, accounting for 40% and 45% of national emissions of these gases. Additionally, emissions across the broader agrifood value chain, including upstream and downstream beyond the farm, have increased significantly, making agrifood system emissions far greater than those from agriculture alone. This study estimates that in 2021, China's agrifood systems emitted around1.6 billion tonnes of CO_2eq, representing approximately 12% of the country's total GHG emissions.

Multiple pathways exist for mitigating GHG emissions from agrifood systems, including enhancing agricultural productivity, adopting low-carbon technologies, reducing food loss and waste, shifting dietary patterns, and transitioning to cleaner energy sources (Zhang et al., 2023; Liang et al., 2023; Zhu et al., 2022; Xue et al., 2021; Zhang et al., 2021; Hu et al., 2020).

Reducing emissions and enhancing carbon sequestration within China's agrifood systems not only contributes to domestic climate objectives (Zhang et al., 2021; Zhao et al., 2023), but also advances the country's international climate commitments and leadership in global climate governance.

This study aims to: (1) Estimate greenhouse gas emissions and carbon sinks across China's agrifood systems; (2) Summarize key emission reduction strategies and sequestration pathways; (3) Evaluate the effectiveness of these measures using the interdisciplinary model-Agrifood System Model developed by China Agricultural University (CAU-AFS Model); (4) Propose forward-looking policy recommendations to support the low-carbon transformation of China's agrifood systems.

6.2 Accounting for Carbon Emissions and Sinks in China's Agrifood Systems

Since the concept of the agrifood system was introduced, global attention to its carbon emissions has steadily increased. FAO began publishing a global database on carbon emissions from agrifood systems in 2022. However, most research in China remains focused solely on emissions from agricultural production, with limited attention given to the full emissions from the entire agrifood system. To fill this gap, this study combines official Chinese government statistics with the latest emission factor databases to comprehensively estimate carbon emissions across China's agrifood systems. This provides a scientific basis for understanding the system's carbon emissions and informing effective mitigation strategies.

6.2.1 Scope, Methodology, and Data Sources

This study adopts a systematic approach to estimate carbon emissions across the entire agrifood system, encompassing three key stages: pre-production, production, and post-production. Pre-production emissions include those generated during the manufacture of agricultural inputs such as fertilizers, pesticides, and plastic films. Production emissions refer to direct emissions from agricultural activities, including crop cultivation and livestock and poultry farming. Post-production emissions cover agricultural product processing, food manufacturing, food services, as well as associated logistics—transportation, storage, wholesale, and retail.

Agricultural production is a significant source of nitrous oxide and methane. This study accounts for emissions of methane (CH_4), nitrous oxide(N_2O), and carbon dioxide (CO_2) across the agrifood systems from 2005 to 2022. Data on agricultural emissions of of methane and nitrous oxide (including enteric fermentation, manure management, methane emissions from rice cultivation, agricultural soil, and straw burning) were obtained from the *National Communications on Climate Change* and the *First Biennial Transparency Report (BTR) on Climate Change* issued by the Ministry of Ecology and Environment. Importantly, the recently released datasets include revisions to the 2005 baseline and report significant increases in carbon emissions from agricultural activities—exceeding 100 million tonnes of CO_2eq between the years of 2018 and 2020-2021.

To estimate energy-related emissions during pre- and post-production, this study utilizes *China's Input-Output Tables* (published by the National Bureau of Statistics) alongside sectoral energy consumption data since 2000. This includes energy use in agriculture, forestry, animal husbandry, and fisheries, as well as emissions from processing of agricultural products, fertilizer and pesticide production, agricultural plastic film and machinery manufacturing, and agriculture-related transport, storage, distribution, and food services.

The primary methodology employed is the emission factor approach, using greenhouse gas emission factors from the National GHG Emission Factors Database, jointly developed by the Ministry of Ecology and Environment and the National Bureau of Statistics. For carbon sink, the analysis focuses on land use, land-use change, and forestry (LULUCF), particularly from forests and grasslands. Carbon sink data are drawn mainly from official reports released by the Ministry of Ecology and Environment.

6.2.2 Historical Trends in Carbon Emissions from China's Agrifood Systems

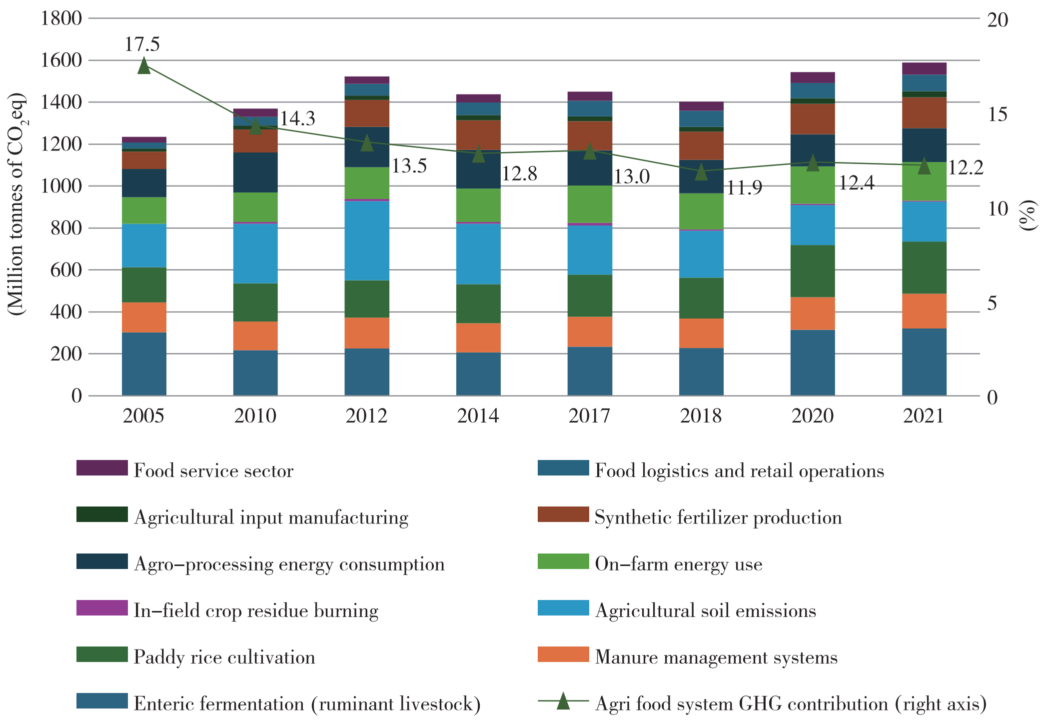
China's agrifood systems emit significantly more GHG than agricultural production alone. As shown in Figure 6-1, total carbon emissions from the agrifood systems rose from 1.2 billion tonnes of CO_2eq in 2005 to 1.6 billion tonnes of CO_2eq in 2021—an overall increase of 28.7%, with an average annual growth rate of 1.6%. In contrast, emissions from agricultural activities (including enteric fermentation, manure management, rice cultivation, farmland emissions, and crop residue burning) rose more slowly, from 820 million tonnes of CO_2eq to 930 million tonnes of CO_2eq, a 13.4% increase.

The expansion of agricultural supply chains has led to increased energy consumption, especially in pre- and post-production stages, such as input production (fertilizers, pesticides, plastic mulch), agricultural machinery use, processing, transportation, storage, wholesale, retail, and catering. Emissions from these energy-related activities surged from 416 million tonnes of CO_2eq in 2005 to 660 million tonnes of CO_2eq in 2021, marking a 58.7% increase and an average annual growth rate of 2.9%. This rise has been the primary driver of overall emissions growth in the agrifood systems. As a result, the share of energy-related emissions increased from 33.6% to 41.5%, while the share from direct agricultural activities declined from 66.4% to 58.5% over the same period.

However, the agrifood systems' share of total GHG emissions decreased from 17.5% in 2005 to 12.2% in 2021, reflecting a slower growth rate compared to other energy-intensive sectors. Key emission sources—enteric fermentation, manure management, rice cultivation, farmland emissions, energy use in agriculture and processing, and fertilizer production—together account for roughly 90% of the agrifood systems' total emissions. Between 2005 and 2021, emissions from several key components of China's agrifood systems grew markedly. Emissions from rice cultivation increased from 167 million to 248 million tonnes of CO_2eq, energy use in agriculture, forestry, and fisheries rose from 126 million to 185 million tonnes of CO_2eq, and fertilizer production expanded from 83 million to 146 million tonnes of CO_2eq, reflecting growth rates of 48.9%, 46.9%, and 76.4%, respectively.

In contrast, emissions from energy use in food processing, though substantial, grew more slowly—from 136 million tonnes of CO_2eq in 2005 to 162 million tonnes of CO_2eq in 2021, representing a more modest increase of 19%. Although smaller in overall contribution, emissions from pesticides, plastic mulch, agricultural machinery, transportation, storage, wholesale, retail, and catering were doubled over the same period. For instance, emissions from pesticides rose from 14 million to 30 million tonnes of CO_2eq, plastic mulch from 29 million to 78 million tonnes of CO_2eq, and downstream activities such as transport, storage, and retail from 29 million to 59 million tonnes of CO_2eq.

Figure 6-1 Greenhouse gas emissions from China's agrifood systems (2005-2021) and their contribution to total national emissions



Data sources: Agricultural emissions from official reports by the Ministry of Ecology and Environment; energy-related emissions estimated by the authors.

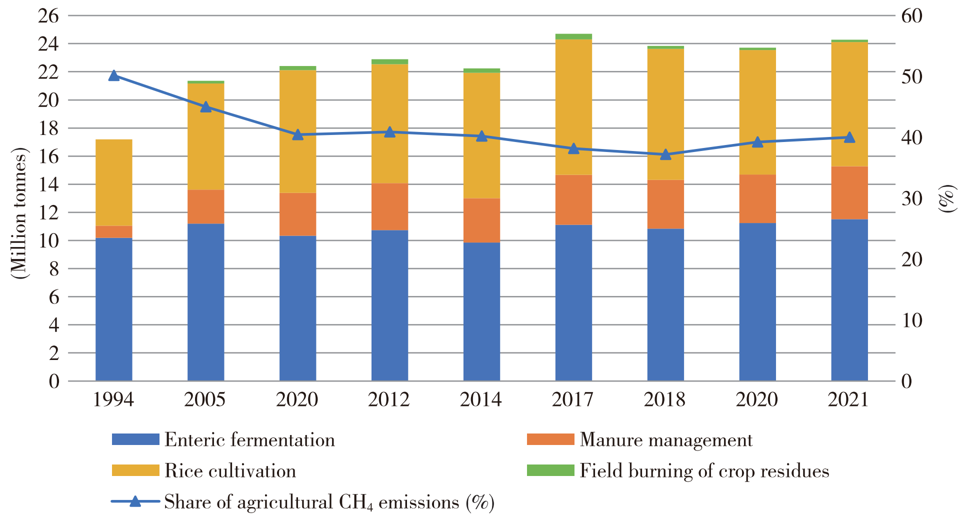
Agricultural activities remain the largest source of emissions within the agrifood systems, with nitrous oxide and methane as the primary and secondary GHG contributors, respectively. As shown in Figure 6-2, total methane emissions from agricultural sources rose from 21.4 million tonnes (600 million tonnes of CO_2eq) in 2005 to 24.7 million tonnes (690 million tonnes of CO_2eq) in 2017, a 43.7% increase,before stabilizing at around 24 million tonnes (670 million tonnes of CO_2eq) in recent years.

Livestock remains the dominant driver of agricultural methane emissions, accounting for 60-65% of the total. Within this, enteric fermentation contributes 47.4%, while manure management, the faster-growing component, contributes 15.5%. Methane emissions from crop cultivation, primarily from rice paddies,make up 35-40% of the total but have declined slightly, dropping from 9.6 million tonnes (270 million tonnes of CO_2eq) in 2017 to 8.9 million tonnes (248 million tonnes of CO_2eq) in 2021, an 8% reduction. In contrast, crop residue burning accounts for only 0.6% of agricultural methane emissions.

As shown in Figure 6-3, nitrous oxide emissionsre are mainly associated with farmland. Emissions from farmland peaked in 2012 at 1.5 million tonnes (390 million tonnes of CO_2eq) before falling to 0.9 million tonnes (250 million tonnes of CO_2eq) in 2021. Their share in total agricultural nitrous oxide emissions fell from 65% in 2005 to 45% in 2021.

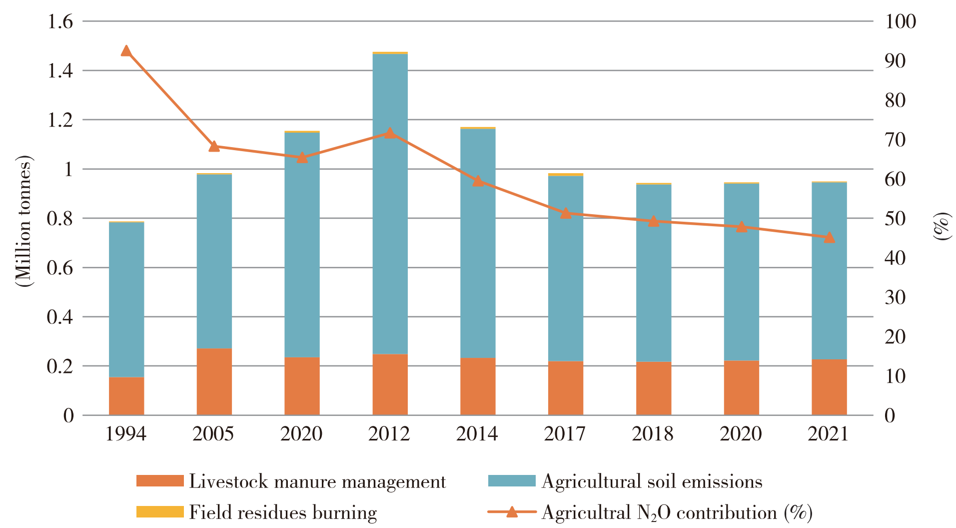
Despite the decline, farmland remained the dominant source, contributing around 80% of total nitrous oxide emissions, peaking at 1.2 million tonnes (320 million tonnes of CO_2eq) in 2012 and declining to 0.7 million tonnes (190 million tonnes of CO_2eq) in 2021, or 76% of the total. Emissions from manure management remained stable at around 0.2 million tonnes (53 million tonnes of CO_2eq), accounting for about 20% of the total, while crop residue burning contributed a negligible 0.004 million tonnes (1.1 million tonnes of CO_2eq) in 2021, or just 0.4% of the total.

Figure 6-2 Methane (CH_4) emissions from China's agricultural activities (2005-2021)



Data sources: Official reports published by the Ministry of Ecology and Environment (MEE) of China: National Communications on Climate Change &First Biennial Transparency Report on Climate Change

Figure 6-3 Nitrous oxide (N_2O) emissions from China's agricultural activities (2005-2021)



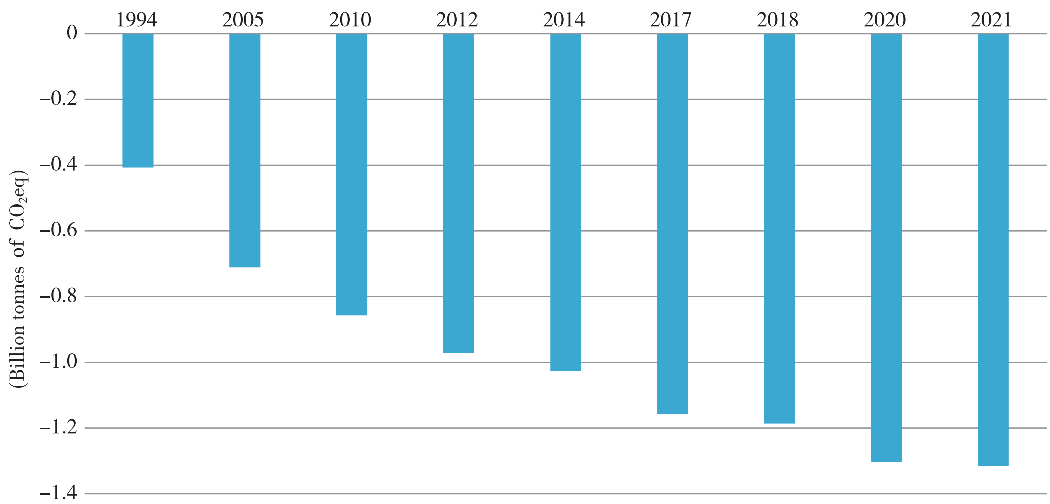
Data sources: Official reports published by the Ministry of Ecology and Environment (MEE) of China:National Communications on Climate Change &First Biennial Transparency Report on Climate Change

6.2.3 Historical Trends of Carbon Sink from Land Use, Land Use Change and Forestry (LULUCF)

China's LULUCF carbon sink has strengthened markedly over the past three decades. According to China's *First Biennial Transparency Report on Climate Change*, net GHG sink from LULUCF rose from 407 million tonnes of CO_2eq in 1994 to 1.3 billion tonnes of CO_2eq in 2021, a gain of 908 million tonnes (Figure 6-4). Specifically, in 2021: Forests absorbed 877 million tonnes of CO_2eq (66.7 % of the total sink); Agricultural lands absorbed 106 million tonnes of CO_2eq (8.1 %); Grasslands absorbed 64.08 million tonnes of CO_2eq (4.9 %); Wetlands, by contrast, became a small net source, emitting 6.5 million tonnes of CO_2eq—because they took up 24.6 million tonnes of CO_2eq of carbon but released 31.1 million tonnes of CO_2eq of methane.

Peking University projects that afforestation efforts between 1994 and 2018 generated a carbon sink of 0.24 ± 0.03 Gt C per year (≈0.84 billion tonnes of CO_2eq). If China achieves its official afforestation targets and maintains current sinks elsewhere, this annual uptake could grow to 0.35 ± 0.04 Gt C (≈1.28 billion tonnes of CO_2eq) by (He, et al., 2024), representing an additional 440 million tonnes of CO_2eq in annual sequestration compared to current levels. Under this scenario, future carbon sinks from LULUCF would reach about 1.8 billion tonnes of CO_2eq.

Figure 6-4 China's land use, land use change and forest (LULUCF) carbon sink



Source: The National Communications on Climate Change and the First Biennial Transparency Report on Climate Change issued by the Ministry of Ecology and Environment of the People's Republic of China.

6.3 Carbon Emission Reduction and Sink Enhancement Measures in China's Agrifood System

6.3.1 Emission Reduction Measures in China's Agrifood Systems

Reducing carbon emissions in agricultural activities mainly relies on technological innovations, including increasing agricultural productivity, improving crop cultivation technology, implementing fertilizer reduction and conservation tillage, and optimizing feed formulation to reduce methane emissions from ruminants. Additional strategies involve restructuring food production and consumption patterns, minimizing food loss and waste, cutting emissions along the food supply chain (transportation, processing, storage, and packaging), improving energy efficiency, and increasing the use of non-fossil energy, all of which can effectively reduce energy consumption and greenhouse gas emissions from agrifood systems.

Improving agricultural productivity is central to these efforts. In the livestock sector, enhancing animal production performance, primarily through breeding, can yield the dual benefits of higher productivity and lower carbon emissions. This involves improving genetic traits related to yield, feed conversion, and emission intensity. According to De Haas Y et al. (2021), selective breeding could enhance the performance of Dutch dairy cattle by 13% and reduce methane emission intensity by 24% between 2018 and 2050. In China, the animal husbandry sector has grown significantly over the past two decades, meeting growing demand for meat, eggs, and milk, while also reducing carbon emission intensity per unit of product. Recently, the adoption of intelligent and automated technologies has significantly improved productivity and environmental sustainability. AI is transforming and upgrading the livestock industry by enhancing health monitoring, optimizing outputs, and improving overall farm efficiency (Deepika, 2024). Internet of Things (IoT) systems enable real-time monitoring of temperature, humidity, air quality, and animal behavior, leading to better environment control and productivity.

Methane abatement in rice cultivation is also a key strategy. As analyzed in Chapter 2, water management, fertilization and organic material management, variety selection, and tillage and cultivation techniques can effectively reduce emissions. Emerging technologies, such as AI and gene editing, have made these measures even more effective. AI systems can monitor real-time data on soil moisture, temperature, and fertility in rice paddies, and use machine learning algorithms to project methane emissions and optimize water and nutrient management (Huan et al., 2025). Gene editing enables precise modifications of rice traits to regulate root exudates and promote beneficial soil microbes, thereby reducing methane emissions at the source and improving sustainability.

Low-carbon livestock practices also contribute significantly to emission reduction. As analyzed in Chapter 3, these technologies include sustainable breeding, improved feeding management, rumen regulation, and manure recycling. AI-driven precision feeding and sustainable breeding strategies improve feed efficiency and reproductive efficiency, while reducing methane emissions. For example, it can raise pig feed conversion by 8-12% and shorten the time to market by 5-7 days (Banhazi et al., 2012). Rumen regulation adjusts fermentation, pH level, and microbial populations to enhance feed digestibility and reduce methane. Strategies include using feed additives like oils, microbial agents, halogenated compounds, seaweed, or developing rumen methanogen vaccines. Research has shown that altering rumen fermentation patterns is one of the most effective methods to reduce methane emissions (Haque M, 2018). Manure utilization focuses on improved storage, treatment, and gas recovery systems, including biogas projects, and promoting biogas use for heating, electricity, transport, or integration into municipal grids.

Fertilizer optimization is also essential. Techniques such as precision fertilization, fertigation, and deep drip irrigation reduce nitrogen loss and boost uptake efficiency (Gu et al., 2023; van Wesenbeeck et al., 2021). Cui et al. (2018) reported that 20.9 million farmers across 452 counties increased grain yields by 10.8-11.5% while reducing nitrogen fertilizer use by 14.7-18.1% from 2005 to 2015. Gu et al. (2023) synthesized data from 1,521 experimental sites and identified 11 key measures for reducing nitrogen loss, which can cut nitrous oxide emissions by 30-70%, while increasing yields by 10-30% and nitrogen use efficiency by 10-80%.Complementary practices such as reduced or no-tillage, micro-topography reshaping, land cover, and crop rotation also mitigate erosion and protect soil health (Wang et al., 2023; Li et al., 2002). Global research confirms that improving nitrogen use efficiency is critical to reducing fertilizer emissions. However, this must be coordinated with decarbonizing fertilizer production. Gao & Serrenho (2023) estimate that existing technologies could reduce emissions from fertilizers to one-fifth of current levels by 2050.

Reducing food loss and waste holds substantial potential for emission reduction. As highlighted in Chapter 5, it is one of the most cost-effective strategies. Springmann et al. (2018) modeled the food system pathways and found that halving or reducing food loss by 75% by 2050 could reduce GHG emission reductions by 6%-16% and 9%-24%, respectively, under the sustainable development goals framework.

Dietary changes are also critical. Life cycle studies show that beef has a GHG intensity 5-10 times that of pork and poultry, and 50-100 times that of legumes (Poore et al., 2018). Shifting toward plant-based diets is therefore important for low-carbon of agrifood systems (Roe et al., 2021). China's *Outline of Food and Nutrition Development in China (2025-2030)*, issued by the Ministry of Agriculture and Rural Affairs in 2025, proposes this shift by promoting poultry, stabilizing beef production, expanding aquaculture, and boosting the consumption of whole grains, fresh corn, and quality potatoes.

Energy efficiency and clean energy adoption across the entire agrifood value chain are also vital. Since 2000, energy efficiency has doubled in agrifood systems. Between 2005 and 2021, non-fossil energy developments reduced 1.73 billion tonnes of CO_2 emissions in 2021 alone. By 2025, non-fossil energy sources are expected to supply 20% of total energy and 39% of electricity.

Other measures such as intercropping, crop rotation, and spatial optimization can reduce emissions while maintaining yields. Xie et al. (2023) found that optimizing agricultural spatial layout could reduce irrigation and emissions by 6.5%, and increase farmers' income by 4.5%. Zhang et al. (2019) proposed an integrated crop and livestock model in which livestock manure supplies half of the crop nitrogen need, keeping emissions within land capacity. Market-based tools such as carbon taxes and trading also offer mitigation potential. Tang et al. (2019) showed that modest agricultural carbon taxes could reduce crop and livestock emissions by 16% and 33%, respectively, in northern China's Loess Plateau.

6.3.2 Carbon Sink Enhancement Measures

China has made substantial progress in enhancing carbon sinks through forestry ecological restoration, improved farmland management, ecological carbon sequestration technologies, and grassland protection. To further increase carbon sequestration, a suite of additional measures must be implemented.

Forestry ecological restoration has played a crucial role in enhancing carbon sinks through large-scale national initiatives launched since the 1970s. These include the Three-North Shelterbelt Program, the Yangtze and Pearl River Shelterbelt Projects, the Natural Forest Protection Project, the Grain for Green Project, and the Beijing-Tianjin Sandstorm Source Control Project. Designed to protect the environment and restore ecosystems, these projects have made substantial contributions. According to national forest inventories, China's planted forests now cover approximately 79.5 million hectares, with a total forest stock volume of 17.5 billion cubic meters. The FAO (2020) reports that China accounted for about 25% of the world's new green areas between 2010 and 2020, making it the largest global contributor. Over the past decade, these restoration projects have sequestered an estimated total of 3.3 ± 1.6 billion tonnes of CO_2eq (Lu et al., 2018).

Scientific farmland management has also played a pivotal role. China's farmland spans 1.9 billion mu (around 128.6 million hectares), accounting for nearly 10% of the world's total. Since the early 21st century, practices such as reduced or no-tillage, returning crop residues to the fields, applying organic fertilizers, and adopting efficient irrigation techniques have enhanced soil carbon sequestration (Sun et al., 2010; Yu et al., 2012; Xie et al., 2010). No-till farming minimizes soil disturbance, preserves soil aggregates, and increases organic carbon accumulation (Six et al., 2000, 2002). Diversified crop rotations and surface residue coverage further increase the inputs of exogenous organic matter, improving the soil's carbon storage potential (Tiefenbacher et al., 2021). Based on 4,200 soil samples from 60 typical agricultural counties, contributions to carbon stock growth were estimated at 40% from crop residue return, 30% from fertilization, and 30% from root biomass. Modeling results indicate that returning 50% of crop residues to the soil could boost soil carbon storage by 0.6 Pg C, or 550 million tonnes, over the next two decades (Fang et al., 2015).

Ecological carbon sequestration strategies are gaining attention, especially in response to the challenges posed by managing large volumes of agricultural and forestry residues, which often contribute to environmental degradation. One promising solution is Ecological Carbon Capture, Utilization, and Storage (Eco-CCUS), which aims to optimize the reuse of biomass residues and promote their moderate return to fields. Eco-CCUS could theoretically enhance annual carbon sinks by 380 million tonnes of CO_2, equivalent to a 36.9% increase in China's current rate of terrestrial ecosystem CO_2 fixation (Li et al., 2023). In particular, the seasonally frozen soils of Northeast China, where decomposition of organic matter is slowed, are especially well-suited for this approach. Compared to industrial carbon capture methods, Eco-CCUS is significantly more cost-effective and helps reduce emissions from the burning of crop residues and forestry waste (Li, M et al., 2023).

Grassland protection and restoration also hold immense potential for enhancing carbon sink. China's grasslands cover about 290 million hectares, accounting for 30.5% of the country's land area and playing a vital role in terrestrial carbon cycles (Fang et al., 2018). The government has launched several initiatives such as the Grain for Green and Grazing to Grassland Restoration programs, natural grassland enclosures, and efforts to rehabilitate degraded grasslands. These efforts reduce human disturbance and restore ecosystem function. These actions have improved vegetation cover, boosted the input of organic binding agents, and enhanced soil health (Li et al., 2023). Soil aggregates, which are crucial for storing organic carbon, benefit significantly from these practices. By fostering the formation of stable aggregates, these efforts enhance the physical protection of organic carbon, ultimately increasing organic matter content and strengthening the soil organic matter and strengthen the carbon sequestration capacity of grassland soils (Mustafa et al., 2020; Liu and Yu, 2011).

6.4 Evaluation of the Effectiveness of Emission Reduction Measures in China's Agricultural Food Systems

6.4.1 Interdisciplinary Simulation Model: The CAU-AFS Model

This study employs the Agricultural Food System Model developed by China Agricultural University (CAU-AFS Model) to project future trends in agricultural supply and demand, as well as changes in production, land use, and sectoral value-added across China. Building on this framework, and aligned with the emission reduction strategies discussed earlier in this chapter, the study designs a set of scenarios to evaluate the combined effects of various measures on food production, consumption, and GHG emissions.

The CAU-AFS Model integrates several sub-models and draws upon the strengths of diverse academic disciplines. It includes agricultural partial equilibrium models, general equilibrium models, and specialized modules focused on nutrition and health, natural resources, and environmental impacts. The model aims to tackle major interdisciplinary challenges in transforming the agrifood system and offers timely, effective, and multi-objective policy evaluation for decision-makers.

To simulate the impacts of emission reduction measures, two key models were employed: the China Agricultural Spatial Equilibrium Model and the China Dynamic General Equilibrium Model, both of which include carbon emissions modules.

The China Agricultural Spatial Equilibrium Model is a partial equilibrium model used to simulate future food supply and demand based on the concepts of "big food" and "big resources." It operates within a supply-demand balance framework covering 85 types of agricultural products, processed goods, and by-products. The model assumes market equilibrium is achieved when supply equals demand, with prices determined accordingly. Using 2021 as the base year, the model is run dynamically through 2060 using a recursive dynamic method.

The China Dynamic General Equilibrium Model projects GDP growth by sector and incorporates a carbon emissions module to estimate emissions related to energy consumption. It is solved using the General Algebraic Modeling System (GAMS), allowing for dynamic assessment of the economic and environmental impacts of different emission reduction strategies.

6.4.2 Scenario Design

This study develops two main categories of scenarios: a baseline scenario that serves as a reference point, and a series of scenarios designed to assess the emission reduction impacts of various mitigation strategies under different conditions.

In the baseline scenario, future trends in carbon emissions from the agrifood systems are projected based on anticipated changes in consumption demand, production levels, and value-added output, driven by economic growth, demographic shifts, and technological advancement. According to the National Bureau of Statistics, China's population peaked in 2021, reaching 1.4 billion by 2024, with an urbanization rate of 67% and continued economic expansion. Looking ahead, population size is expected to decline to 1.36

billion by 2035 (with 75% urbanization) and further to 1.1 billion by 2060 (with 82% urbanization), in line with the UN Population Division's medium-variant projection.

Using China dynamic CGE model, national GDP are projected to grow by 3.5%-5.5% annually between 2025 and 2035, slowing to 2.0%-3.5% beyond 2035. Rural household incomes are expected to grow slightly faster than urban incomes, gradually narrowing the income gap. Technological progress is calibrated to historical growth in crop yields and livestock productivity, while the total area of arable land is assumed to remain stable. Energy intensity within the agrifood system is projected to decline by 1% annually, resulting in cumulative reductions of 17.5% by 2035 and 36% by 2060. The share of non-fossil energy in total energy consumption is expected to rise to 25% by 2035 and 37.5% by 2060.

The scenarios evaluate the emission reduction potential of five key strategies discussed in earlier chapters: increasing agricultural productivity, adopting low-carbon technologies, adjusting production structures, reducing food loss and waste, and transitioning to cleaner energy sources. Each strategy is modeled independently and in combination to assess both individual and synergistic impact on emissions.

The productivity improvement scenario (SPROD) explores the impacts of enhanced yields in grain and livestock production, projecting 5% and 10% gains by 2035, rising to 10% and 30% by 2060, respectively. Three separate scenarios simulate the adoption of specific low-carbon technologies. The SRICE scenario examines emission reductions from rice cultivation through improved water management, optimized cultivar selection, conservation tillage practices, efficient fertilization, and organic matter management. The SLIVE scenario models green technologies in livestock systems, including feed optimization through precision feeding and low-protein diets that improve feed conversion by 20% by 2035 and 30% by 2060, rumen regulation through feed additives that reduce enteric fermentation emissions by 25% and 40%, and improved manure management systems that significantly cut nitrous oxide and methane emissions. The SFERT scenario focuses on improving fertilizer use efficiency, thereby reducing nitrous oxide emissions from farmland and lowering upstream industrial emissions by decreasing the demand.

The production structure adjustment scenario (SSTRC) simulates shifts in dietary and agricultural production driven by nutrition and health considerations, promoting the substitution of coarse grains for a portion of rice and the replacement of red meat with poultry or seafood. The SWAST scenario assesses the emission reduction potential of minimizing food loss and waste across the entire agrifood value chain, from production through consumption. The SENRG scenario models improvements in energy efficiency and the increased adoption of non-fossil energy sources across the agrifood sector. Finally, the combined scenario (SCOMB) integrates all six strategies into a comprehensive mitigation pathway to assess their cumulative impact on emissions. Detailed assumptions and modeling parameters for each scenario are presented in Table 6-1 as below.

Table 6-1 Scenario Design

Scenario	Description for the Changes of Productivity and Carbon Emission
Baseline (BASE)	Business-as-usual. Emission factors from agricultural activities remain unchanged. Energy efficiency in the agrifood system improves by 1% annually; energy intensity declines by 0.5% per year—reaching 17.5% in 2035 and 35.8% in 2060. The share of non-fossil energy consumption increases to 25% by 2035 and 37.5% by 2060.
Productivity Enhancement (SPROD)	Gradual yield increases: rice by 5% and livestock by 10% in 2035; rice by 10% and livestock by 30% in 2060. Emission intensity reductions: rice by 5% (2035) and 10% (2060); livestock by 10% (2035) and 30% (2060).

Scenario	Description for the Changes of Productivity and Carbon Emission
Low-carbon Rice Cultivation (SRICE)	Integrated practices include water and nutrient management, improved varieties, and cultivation techniques. Rice yield increases by 5% (2035) and 9% (2060); emission intensity declines by 32% (2035) and 67% (2060).
Livestock Low-carbon Technology (SLIVE)	Rumen management, feed conversion ratio (FCR) improvement (+10% by 2035, +20% by 2060), low-protein diets, and manure management. Emission reductions vary by specy: • Enteric fermentation: -25% (2035), -40% (2060) • Manure management (2035): N_2O (cattle -20%, dairy -24%, swine -32%, sheep -13.5%); CH_4 (cattle/sheep -22.5%, dairy -52.5%, swine -45%) Manure management (2060): N_2O (cattle -32%, dairy -34%, swine -48%, sheep -24%); CH_4 (cattle/sheep -45%, dairy -67.5%, swine -60%)
Fertilizer Use Efficiency (SFERT)	Improvement in fertilizer use efficiency: by 10% (2035) and 20% (2060). Agricultural land emission intensity declines by 10% (2035) and 20% (2060). Fertilizer production emissions drop correspondingly by 10% and 20%.
Nutrition-Driven Restructuring (SSTRC)	Shift from rice/red meat to coarse grains/poultry/aquatic products: • Rice area: -5% (2035), -10% (2060) • White meat consumption: 55% (2035), 70% (2060) of total meat intake
Food Waste Reduction (SWAST)	50% (2035) and 75% (2060) reduction in food loss/waste rates from baseline levels (Chapter 5 reference).
Energy Transition (SENRG)	Enhanced energy efficiency (+22% by 2035, +46% by 2060) with non-fossil energy share rising to 33% (2035) and 66% (2060).
Combined Scenario (SCOMB)	Combines all measures from the scenarios above.

Source: Compiled by the authors.

6.4.3 Future Carbon Emission Projections for China's Agrifood Systems

This study begins by analyzing projected trends in agricultural consumption and production, followed by total carbon emissions from the agrifood systems. These projections serve as a critical baseline for evaluating future emissions and comparing the potential impact of various mitigation scenarios.

Future Consumption and Production Trends (Baseline Scenario)

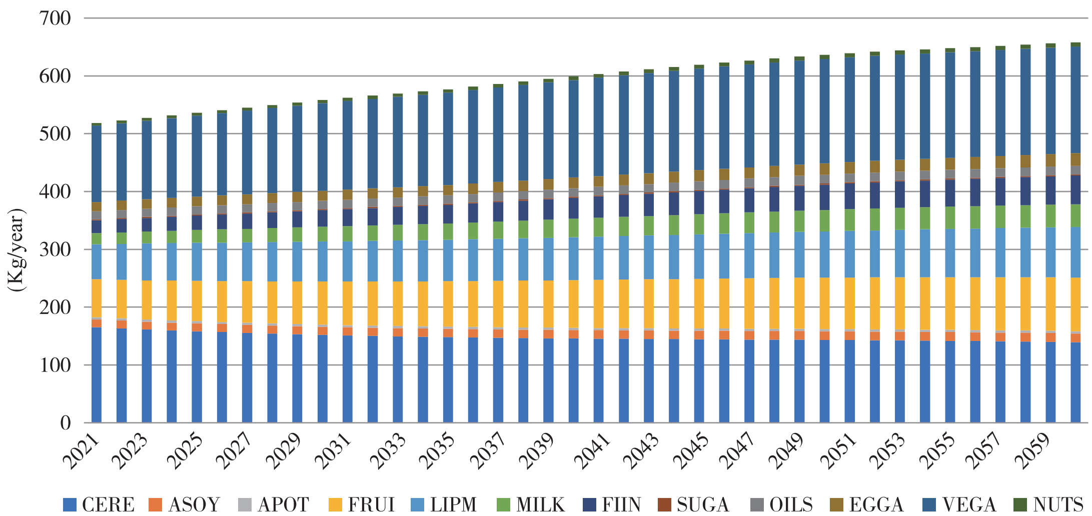
With continued economic development, China's dietary patterns are expected to shift significantly (see Figure 6-5). Between 2025 and 2060, grain consumption will decline, particularly in rural areas, gradually converging with the more stable consumption levels observed in urban populations. Per capita grain consumption, currently at 158 kg per year, is projected to fall to 148 kg by 2035, a 6.4% decline, and further to 139 kg by 2060, representing a 12% decrease from 2021.

In contrast, consumption of aquatic products and dairy products are projected to rise significantly. Per capita aquatic product intake, currently 25 kg per year, is expected to reach 32 kg by 2035 (a 28% increase), and 50 kg by 2060, effectively doubling from 2021 levels. Dairy consumption is project to grow from 22 kg to 28 kg by 2035 (a 29% increase) and to 39 kg by 2060 (a 77% increase). Other foods such as nuts, fruits, livestock and poultry meat, vegetables, and eggs will also experience varying degrees of growth through 2060.

Within meat consumption, beef, mutton, and poultry are expected to grow more rapidly, while pork consumption will stabilize. Rising demand for animal-sourced foods will boost continued growth in livestock production and sustain the demand for feed grains, although this demand will begin to plateau after 2035. As the population declines and urbanization accelerates, direct grain consumption will decrease, while overall food consumption will grow more slowly than per capita rates.

Production trends will largely mirror these changes in consumption. Compared to 2021, rice and wheat production are projected to fall by 26% and 11% by 2060, respectively, driven by reductions in planting areas of 35% and 20%. Conversely, corn planting area and output are expected to rise by 6% and 13%, respectively. In the livestock sector, dairy production is projected to surge by 51% by 2060, with beef and mutton increasing by 25% and 22%, respectively. Poultry, egg, and pork production will see relatively modest growth (see Figure 6-6).

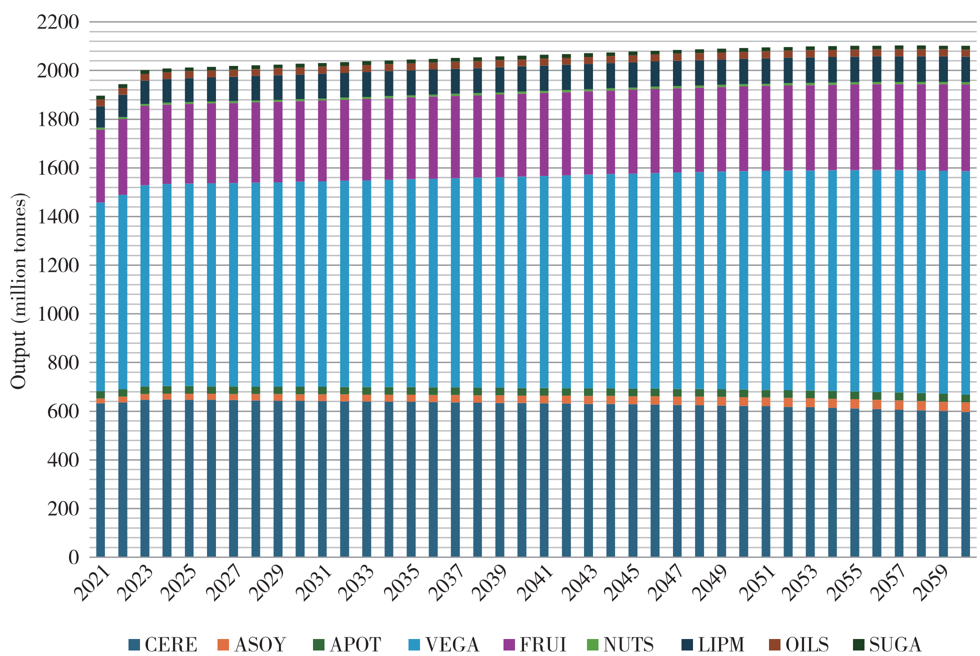
Figure 6-5 Per capita food consumption in China (2021-2060)



Note: CERE (cereals), ASOY (beans), APOT (potatos), FRUI (fruits), LIPM (livestock meat products), MILK (milk), FIIN (aquatic products), SUGA (sugar), OILS (plant oils), EGGA (eggs), VEGA (vegetable), NUTS (nuts).

Source: CAU-AFS model simulation results.

Figure 6-6 Agricultural output in China (2021-2060)



Note: CERE (cereals), ASOY (beans), APOT (potatos), FRUI (fruits), LIPM (livestock meat products), MILK (milk), FIIN (aquatic products), SUGA (sugar), OILS (plant oils), EGGA (eggs), VEGA (vegetable), NUTS (nuts).

Source: CAU-AFS model simulation results.

Economic Growth Trends

The growth of GDP within China's agrifood systems GDP growth is projected to gradually slow over time. Agricultural GDP is expected to grow by an average annual rate of around 3% between 2025 and 2030, before decelerating to 2-3% from 2030 to 2040, and further to 1-2% from 2040 to 2060. GDP growth in fertilizer and pesticide sectors is expected to follow similar trends, while food processing sector will grow at a slightly faster rate. Sub-sectors such as agricultural machinery, plastic mulch, transportation, storage, wholesale, retail, and catering are projected to expand more rapidly. These downstream sectors are expected to grow at an average annual rate of 5-6% from 2025 to 2035, 4% from 2035 to 2045, and 2-3% from 2045 to 2060.

Carbon Emission Trends

Total carbon emissions from the agrifood systems are projected to rise before eventually stabilizing. Emissions are projected to increase from 1.6 billion tonnes of CO_2eq in 2021 to approximately 1.8 billion tonnes by 2037, and continue rising gradually to 1.9 billion tonnes by 2060, an overall increase of 18.4% compared to 2021 (see Figure 6-7). Emissions from agricultural activities will grow more slowly, rising from 0.9 billion tonnes of CO_2eq in 2021 to 1.0 billion tonnes by 2060, representing an 11% rise. Faster GDP growth in the broader agrifood system, relative to core agriculture production, will drive increased inputs such as fertilizers, pesticides, and machinery, and will lengthen supply chains, particularly in downstream sectors like food processing, transportation, storage, retail, and catering. These developments will contribute to higher energy consumption and associated emissions. However, improvements in energy efficiency and a growing share of non-fossil energy, rising to 33% by 2035 and 66% by 2060, will moderate the growth of energy-related emissions. These emissions are projected to rise from 650 million tonnes of CO_2eq in 2021 to around 800 million tonnes by 2034, peaking at 870 million tonnes in 2045 (a 34% increase from 2021), before declining slightly to 850 million tonnes by 2060.

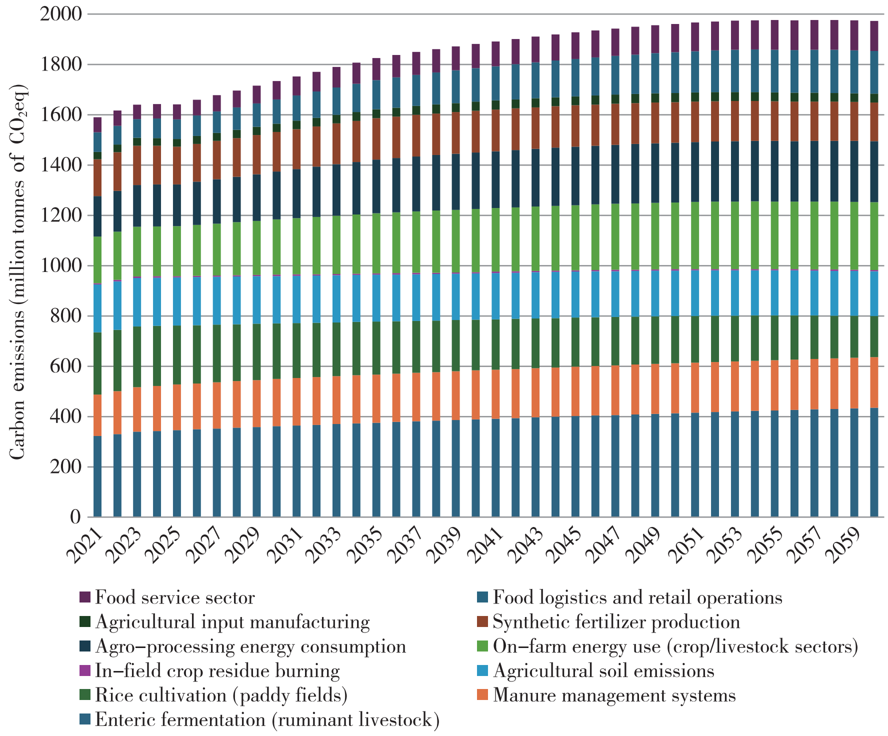
Methane and Nitrous Oxide Emissions

Emissions of methane and nitrous oxide from agriculture are expected to remain stable overall. With rice consumption and production declining, driven by reduced planting areas and yield improvements, methane emissions from rice paddies are projected to decrease significantly to 5.7 million tonnes (160 million tonnes of CO_2eq) by 2060, a 35% reduction from 2021. Methane emissions from crop residue burning will also fall by 7%.

Conversely, increasing livestock production, especially in beef, mutton, and dairy, will raise methane emissions from enteric fermentation and manure management, though the pace of growth will slow over time. Methane emissions from enteric fermentation are projected to rise by 16% by 2035 and 35% by 2060, while emissions from manure-related are expected to increase by 18% by 2035 and 23% by 2060. In total, agricultural methane emissions will stabilize at 25.4 million tonnes (710 million tonnes of CO_2eq) by 2035 and 26 million tonnes (760 million tonnes of CO_2eq) by 2060, representing increases of 5% and 7% from 2021, respectively (see Figure 6-8).

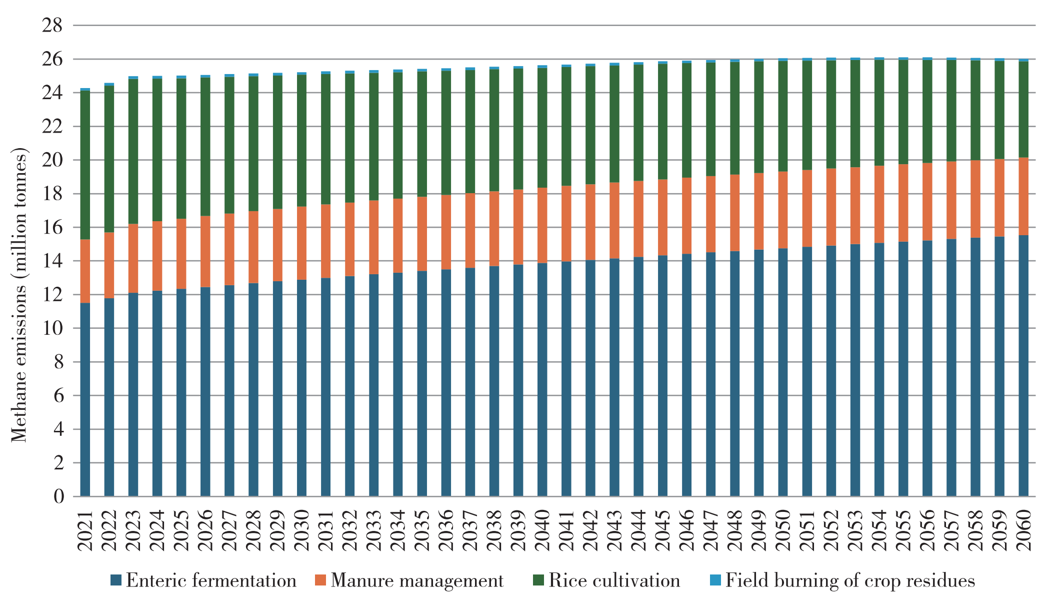
Nitrous oxide emissions(NO_2) will remain relatively constant, fluctuating around 0.95 million tonnes (250 million tonnes of CO_2eq) (see Figure 6-9). Farmland emissions are projected to decline slightly, reaching 0.7 million tonnes (185 million tonnes of CO_2eq) by 2035 and 0.67 million tonnes (178 million tonnes of CO_2eq) by 2060—a reduction of 3% and 7%, respectively. In contrast, nitrous oxide emissions from manure management will increase, reaching 0.26 million tonnes (68.9 million tonnes of CO_2eq) by 2035 and 0.27 million tonnes (71.6 million tonnes of CO_2eq) by 2060, representing increases of 13% and 21%.

Figure 6-7 Projected carbon emissions from China's agrifood system (2021-2060)



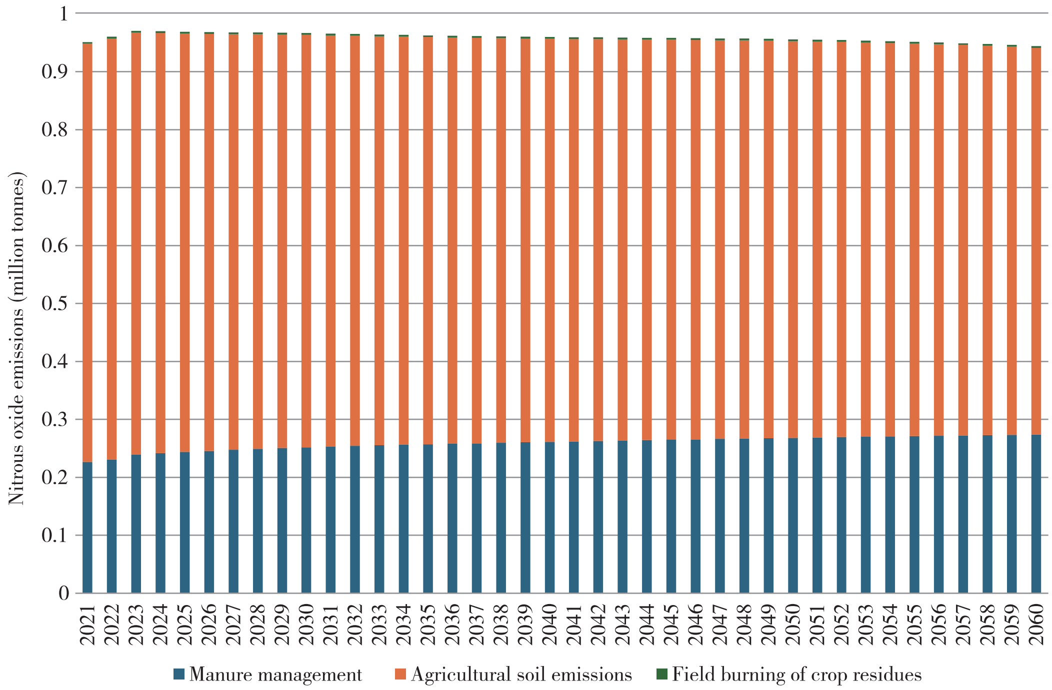
Source: CAU-AFS model simulation results.

Figure 6-8 Projected methane(CH_4) emissions from agricultural activities in China, 2021-2060



Source: CAU-AFS model simulation results.

Figure 6-9 Projected nitrous oxide emissions(NO_2) from agricultural activities in China, 2021-2060



Source: CAU-AFS model simulation results.

6.4.4 Simulated Emission Reduction Effects and Yield Impacts of Various Measures

Building on projections of future carbon emissions from the agrifood system, this study simulates the emission reduction and yield impacts of various mitigation measures. Overall, all the measures contribute to reducing GHG emissions, with their effects that become more pronounced over time.

Emission Reduction Effects:

All scenarios result in significant reductions in agrifood system emissions (see Figure 6-10). In the Productivity Improvement (SPROD) scenario, increased productivity lowers emission intensity, leading to total emissions of 1.7 billion tonnes of CO_2eq by 2035 and 1.8 billion tonnes of CO_2eq by 2060, approximately 5% below the baseline.

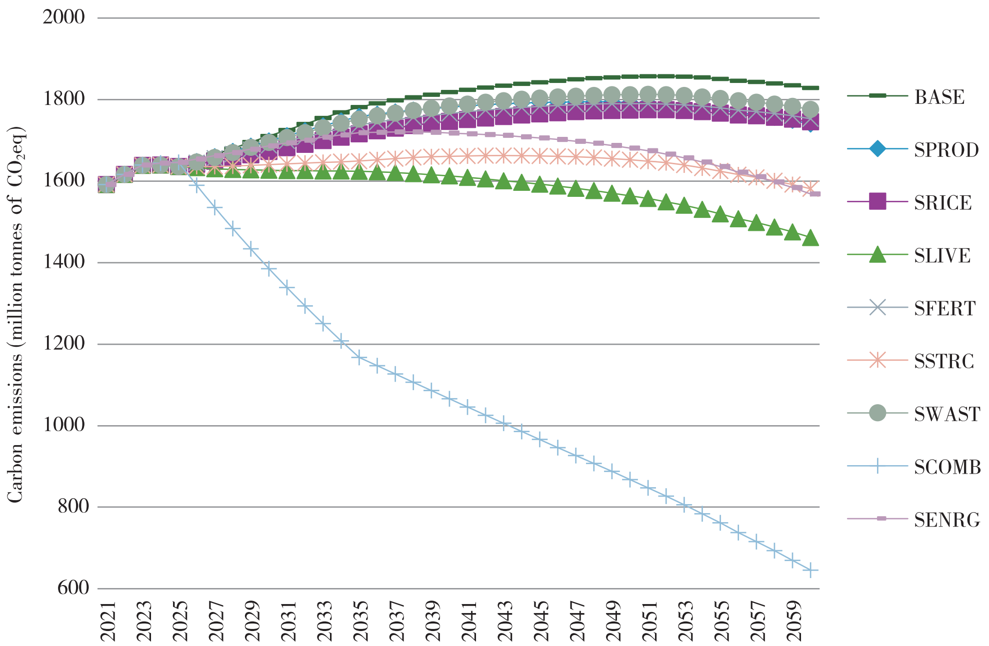
The Rice Emission Reduction (SRICE) scenario reduces emissions by 24 million tonnes of CO_2eq in 2035 and 84 million tonnes of CO_2eq in 2060, accounting for 1.3% and 4.8% of total emissions from agrifood systems respectively.

The Livestock Green Technologies (SLIVE) scenario, targeting one of the major emission sources, achieves the largest single contribution, reducing emissions by 150 million tonnes of CO_2eq by 2035 and 354 million tonnes of CO_2eq by 2060, equivalent to 8.5% and 19.5% of total emissions from agrifood systems.

The Fertilizer Reduction and Efficiency (SFERT) scenario cuts emissions from fertilizer application and production by 44 million tonnes of CO_2eq in 2035 and 75 million tonnes of CO_2eq in 2060, representing 2.5% and 4.1% reductions of carbon emissions from agrifood systems, respectively.

Together, these green technologies achieve a 15% reduction of carbon emissions from agrifood systems by 2035 and 28% by 2060, making them the most promising set of mitigation measures identified in this study.

Figure 6-10 Greenhouse gas emission trends in China's agrifood systems under different scenarios



Note: Baseline (BASE), Productivity Enhancement (SPROD), Low-carbon Rice Cultivation (SRICE), Livestock Low-carbon Technology (SLIVE), Fertilizer Efficiency (SFERT), Nutrition-Driven Restructuring (SSTRC), Food Waste Reduction (SWAST), Energy Transition (SENRG), Combined Scenario (SCOMB).
Source: CAU-AFS model simulation results.

The Production Structure Adjustment (SSTRC) scenario, guided by nutritional and health considerations, shifts production toward coarse grains, legumes, and poultry, while reducing outputs of rice, wheat, and red meat. This transition cuts emissions by 133 million tonnes of CO_2eq in 2035 and 247 million tonnes of CO_2eq in 2060 comparing the baseline representing 7.5% and 13.5%, respectively.

The Reduced Food Loss and Waste (SWAST) scenario lowers emissions by 30 million tonnes of CO_2eq in 2035 and 52 million tonnes of CO_2eq in 2060, equivalent to 1.6% and 2.9% reductions.

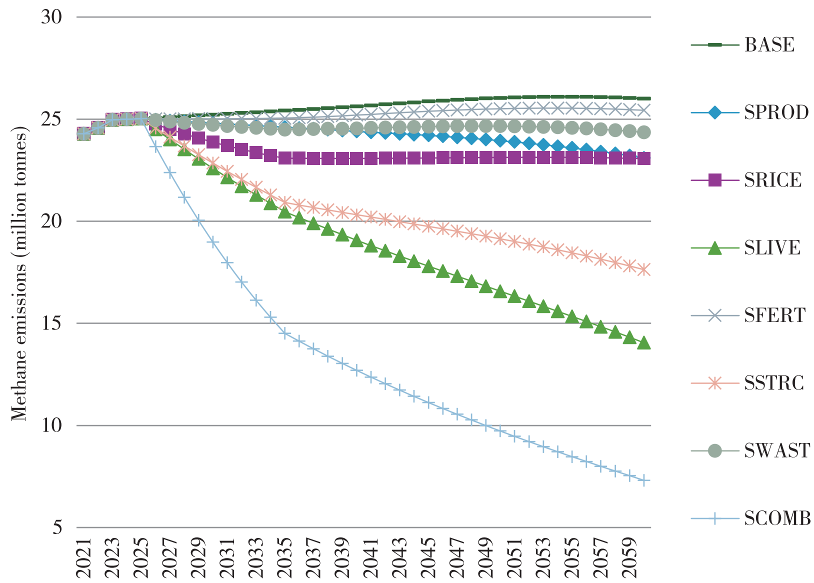
The Energy Transition (SENRG) scenario, which emphasizes improvements in energy efficiency and increased adoption of green energy, leads to emission reductions of 123 million tonnes of CO_2eq in 2035 and 454 million tonnes of CO_2eq in 2060, or 6.9% and 24.8%, respectively.

In the Combined Scenario (SCOMB), all measures are implemented together, resulting in a cumulative reduction of 610 million tonnes of CO_2eq by 2035, 34.4% below the baseline, and 1.18 billion tonnes of CO_2eq by 2060, 64.4% below the baseline. Under this scenario, total emissions fall to just 650 million tonnes of CO_2eq by 2060.

Methane and Nitrous Oxide Reductions:

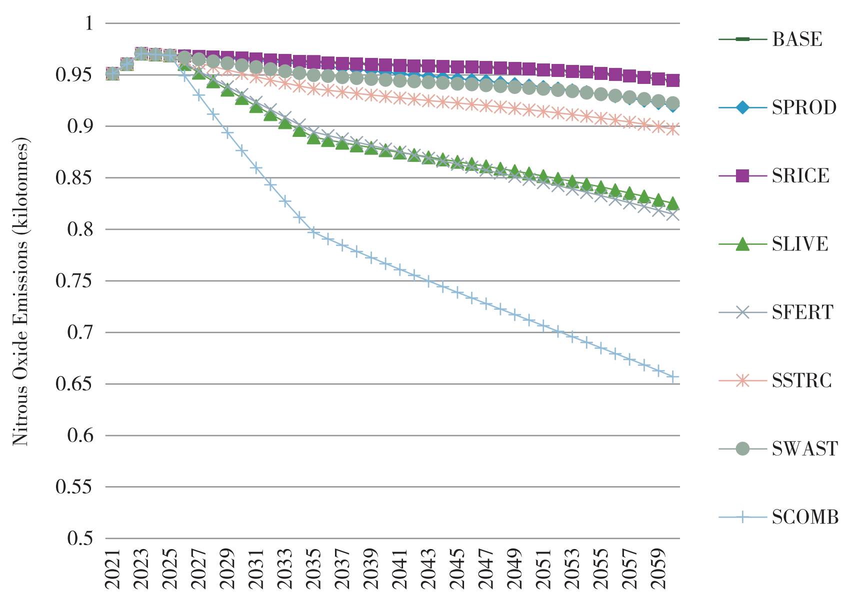
All scenarios contribute to reductions in methane and nitrous oxide emissions from agriculture (see Figures 6-11 and 6-12). Under the SPROD scenario comparing the baseline methane emissions fall by 3.2% in 2035 and 11.2% in 2060. The SRICE achieves reductions of 9.2% and 11.3% in the same years. The SLIVE delivers the most significant impact, lowering methane emissions by 19.5% in 2035 and 46.0% in 2060. The SSTRC follows, with reductions of 17.7% and 32.2%, while the SWAST cuts methane by 3.6% and 6.4%. In the SCOMB scenario, methane emissions decline to 16.7 million tonnes (470 million tonnes of CO_2eq) in 2035 and to 7.3 million tonnes (200 million tonnes of CO_2eq) by 2060, representing reductions of 42.9% and 72.9% from the baseline, respectively.

Figure 6-11 Methane(CH_4) emission trends from agricultural activities under different scenarios in China



Note: Baseline (BASE), Productivity Enhancement (SPROD), Low-carbon Rice Cultivation (SRICE), Livestock Low-carbon Technology (SLIVE), Fertilizer Efficiency (SFERT), Nutrition-Driven Restructuring (SSTRC), Food Waste Reduction (SWAST), Energy Transition (SENRG), Combined Scenario (SCOMB).
Source: CAU-AFS model simulation.

Figure 6-12 Trends in nitrous oxide emissions(NO_2) from agricultural activities in China under different scenarios



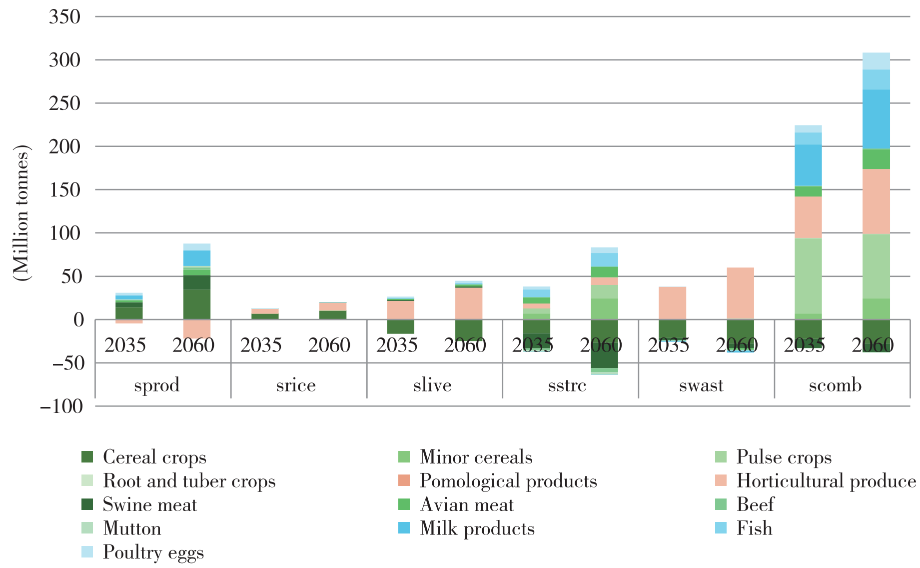
Note: Baseline (BASE), Productivity Enhancement (SPROD), Low-carbon Rice Cultivation (SRICE), Livestock Low-carbon Technology (SLIVE), Fertilizer Efficiency (SFERT), Nutrition-Driven Restructuring (SSTRC), Food Waste Reduction (SWAST), Energy Transition (SENRG), Combined Scenario (SCOMB).
Source: CAU-AFS model simulation.

Reductions in nitrous oxide are comparatively smaller. The SLIVE scenario reduces manure-related nitrous oxide emissions by 7.6% in 2035 and 12.6% in 2060, while the SFERT cuts emissions by 7.1% and 13.7%. The SPROD, SSTRC, and SWAST scenarios show more modest declines of 2.6%, 5%, and 2.3% by 2060, respectively. In the SCOMB scenario, nitrous oxide emissions decrease to 0.76 million tonnes (200 million tonnes of CO_2eq) by 2035 and to 0.66 million tonnes (170 million tonnes of CO_2eq) by 2060, corresponding to reductions of 16.6% in 2035 and 29.4% in 2060 from baseline levels.

Agricultural Production Impact

Mitigation measures also influence agricultural production through a range of mechanisms (see Figure 6-13). In the SPROD scenario, productivity improvements by 2035 increase staple grain yields by 14.3 million tonnes (2.3%). Livestock production sees significant gains: pork rises by 5.6 million tonnes (9.1%), poultry by 2.2 million tonnes (7.9%), dairy by 4.8 million tonnes (9.3%), and eggs by 2.7 million tonnes (7.4%). The SRICE scenario raises total grain output by 6.9 million tonnes (1.1%) through enhanced rice productivity, which in turn allows for a reduction in planting area and an increase in vegetable production by 5.2 million tonnes (0.6%).

Figure 6-13 Changes in agricultural output across scenarios in China



Source: CAU-AFS model simulation results.

In the SLIVE scenario, improved feed efficiency results in slight increases in pork, poultry, and dairy yields (ranging from 1 to 1.6 million tonnes) and modest gains in beef and mutton (around 0.2 million tonnes). At the same time, feed grain demand is reduced, resulting in a decline of 16.5 million tonnes (2.6%) in staple grain output. Meanwhile, vegetable yields rise by 21 million tonnes (2.5%).

Under the SSTRC scenario, by 2060, the output of coarse grains and legumes increases significantly, by 24.5 million tonnes (2.5 times) and 15.5 million tonnes (39.5%), respectively. Poultry and aquatic product yields also rise, by 23.2 million tonnes and 15.8 million tonnes, respectively. However, these gains are accompanied by reductions in staple grain output (down 26.9 million tonnes) and declines in pork, beef, and mutton production, by 29.3 million, 4.5 million, and 3.1 million tonnes, respectively.

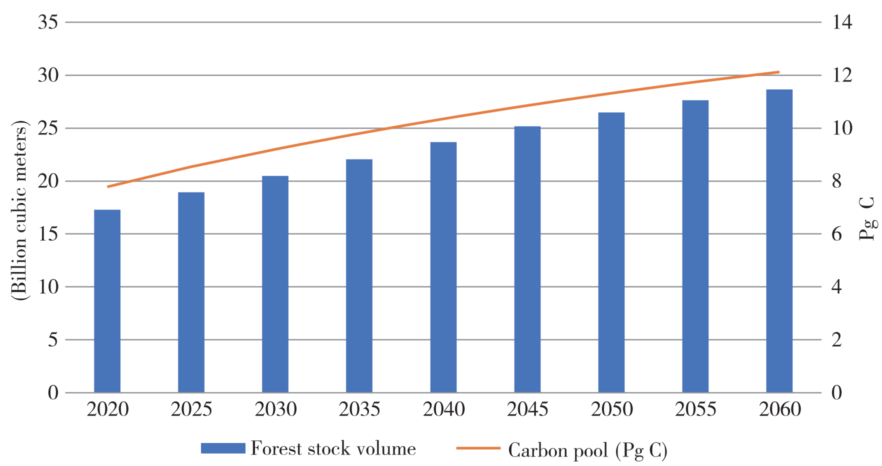
The SWAST scenario leads to a 27.8 million tonnes (4.7%) reduction in staple grain production and a 4-8% decrease in livestock production, including a 5.3 million tonnes decline in pork and a 1.8 million tonnes (8.6%) drop in poultry production.

In the SCOMB scenario, the yields of most products increase, except for staple grains and pork. While the six individual measures, productivity improvement, rice methane reduction, low-carbon livestock technologies, production structure adjustment, reduced food loss and waste, and the combined strategies differ in scale, but follow similar trends from 2035 to 2060, with effects intensifying over time.

6.5 Projection of Future Carbon Sink Potential in China's Agroecosystem

China's forest ecosystems possess considerable potential to enhance carbon sinks. Using an accumulation-stand age growth model for dominant tree species across regions, and incorporating data from the Ninth National Forest Resources Inventory, recent studies have projected the country's forest stock up to 2060. Drawing on established methodologies for projecting forest biomass carbon sinks, the results have been systematically compiled (Fu et al., 2022; see Figure 6-14). Estimates suggest that forest stock will rise to 20.5 billion m^3 by 2030 and further expand to 28.6 billion m^3 by 2060. This represents an increase of 3.5 billion m^3 and 11.6 billion m^3, respectively, compared to the baseline of 17 billion m^3 recorded during 2014-2018.

Figure 6-14 Projection of China's forest stock volume and forest biomass carbon pool from 2020 to 2060



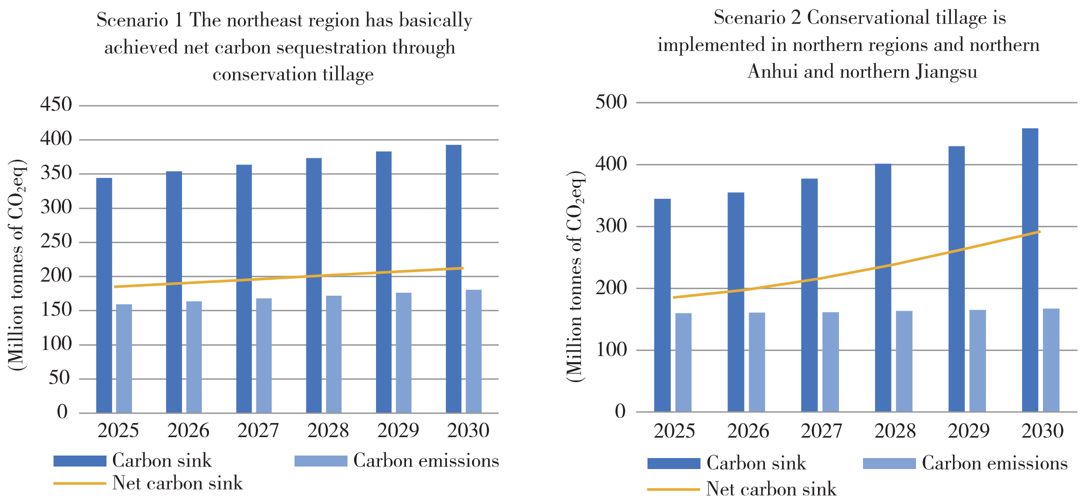
Source: Fu Xiao et al. (2022)

Correspondingly, China's forest biomass carbon pool is projected to grow steadily over the coming decades. By 2030, it will reach 9.3 PgC (1 PgC = 1 billion tonnes of carbon), and by 2060, it is expected to rise to 13 PgC, representing increases of 1.7 PgC and 5.5 PgC compared to the 2014-2018 average of 7.6 PgC. Relative to 2020, this translates to a cumulative increase of 4.3 PgC, with an average annual growth of 0.1 PgC.

Agricultural land also holds substantial potential for enhanced carbon sequestration. Studies have evaluated the effect of conservation tillage on the net carbon sink of farmland in China for the period 2025-2030 under two different scenarios. Scenario 1 assumes widespread adoption of conservation farming in Northeast China, while Scenario 2 extends this adoption to the northern region, northern Anhui, and northern Jiangsu (Xue et al., 2022). According to projections (see Figure 6-15), under Scenario 1, carbon sequestration from conservation tillage increases modestly, reaching 212 million tonnes of CO_2eq by 2030, a 14% rise from 2025. In contrast, Scenario 2 exhibits a more robust growth trajectory, with the net carbon sink expanding to 292 million tonnes of CO_2eq by 2030, approximately 1.6 times the 2025 level.

These simulations underscore the significant potential of conservation tillage to enhance agricultural carbon sinks. To further unlock this potential, it is recommended that conservation tillage be progressively promoted beyond northeastern and northwestern regions to central and southern areas. A comprehensive approach, combining policy incentives, technical training, and widespread guidance, will be key to improving acceptance and adoption across provinces and regions.

Figure 6-15 Projection of China's net carbon sink potential from conservation tillage



Source: Xue Caixia et al. (2022)

Grassland ecosystems also exhibit substantial capacity for increased carbon sequestration. In recent years, the Chinese government has prioritized grassland ecological protection, increased investment, and implemented numerous protection and restoration initiatives. Additionally, an improved subsidy and reward mechanism for grassland ecological conservation has further supported this effort. Studies reveal significant variation in carbon sink potential of grassland under different development scenarios. If current management practices continue, the grassland carbon sink will remain relatively stable, reaching an estimated -127±4.9 million tonnes of CO_2eq by 2030. However, under more proactive strategies, such as large-scale artificial grassland construction or comprehensive grazing bans, the carbon sink capacity is expected to enter a phase of rapid growth followed by steady expansion. Under such enhanced efforts, the grassland carbon sink is projected to reach -213±15 million tonnes and -232±16 million tonnes of CO_2eq by 2030 (Hu, 2023).

6.6 Conclusions and Policy Recommendations

This study calculated the historical carbon emissions from China's agrifood systems and projected future trends based on agricultural product supply and demand as well as expected growth in the GDP of the agrifood systems, projected the total carbon emissions and structural changes of the system. It also systematically reviewed existing mitigation measures and conducted simulation-based analyses to assess the mitigation potential of different strategies. The key conclusions are as follows: GHG emissions from China's agrifood systems remain high and represent a significant share of national emissions. As agricultural production expands and agrifood value chain becomes more complex, carbon emissions have risen markedly, from 1.2 billion tonnes of CO_2eq in 2015 to nearly 1.6 billion tonnes today, now accounting for 12% of China's total emissions. In 2021, methane and nitrous oxide emissions from agricultural activities reached 680 million and 250 million tonnes of CO_2eq, respectively, contributing 40% and 45% of total national emissions for each gas.

Looking ahead, without strong mitigation, emissions from the agrifood systems will continue to rise, posing major challenges to achieving carbon neutrality by 2060. While declining population growth, improved energy efficiency, and increased adoption of non-fossil energy may curb emissions, rising demand for animal products, the expansion of agrifood industry chains, and growing energy consumption will keep overall emissions elevated. Methane emissions from rice cultivation are expected to decrease due to reduced planting area, and nitrous oxide emissions from cropland may decline. However, methane emissions from livestock are projected to grow. Meanwhile, CO_2 emissions from energy use in the agrifood systems are also on the rise, with total GHG emissions anticipated to exceed 1.8 billion tonnes of CO_2eq.

Meanwhile, China's land use, land-use change, and forestry (LULUCF) sector has made strong progress in expanding carbon sinks. Large-scale afforestation, improved farmland management, ecosystem restoration, and grassland protection efforts have all contributed to this increase. In 2021, LULUCF carbon sink rose to 1.32 billion tonnes of CO_2eq. Forests, conservation tillage on croplands, and grasslands hold vast potential for further enhancing carbon sequestration.

However, emissions sources in the agrifood system are diverse and interlinked. The mitigation effect of any single measure remains limited. Thus, integrated and synergistic strategies are essential. If implemented effectively, comprehensive mitigation strategies can significantly reduce emissions while maintaining food production. Promising options include boosting productivity through low-carbon technologies, adjusting production structure, reducing food loss and waste, and accelerating the transition to cleaner energy. By 2060, such an integrated approach could reduce emissions by more than 60%, bringing them down to 650 million tonnes of CO_2eq. However, the current LULUCF carbon sink is insufficient to fully offset these emissions, leaving a gap of nearly 500 million tonnes. If both mitigation and sink enhancement efforts are scaled up, the agrifood systems could not only achieve neutrality but also become a net carbon sink of 1.1 billion tonnes, contributing to national carbon neutrality goal.

Over the past decade, the Chinese government has made substantial progress in promoting green agriculture, with notable reductions in the carbon intensity of the agrifood system. Still, the implementation and adoption of mitigation measures remain limited. Continued and coordinated efforts by government, industry, and society are essential to drive the system's transition to a low-carbon future.

Moving forward, firstly it is critical to set clear carbon reduction and low-carbon development goals for the agrifood systems. Although various policies have supported greener agricultural practices, a specific emissions reduction target remains absent. A strategic roadmap for low-carbon development should be established, supported by scientific monitoring and evaluation frameworks. This includes regular assessments of emissions and carbon sinks, setting phased reduction and sequestration targets, and embedding low-carbon objectives into agricultural and rural development policies. Complementary policy tools should be introduced to support China's 2060 carbon neutrality goal.

Secondly, a multi-pronged approach is needed to reduce emissions while achieving multiple development objectives. Enhancing agricultural productivity offers a dual benefit of boosting output and lowering emissions. Emerging technologies, such as artificial intelligence and modern biotechnology, can support the development and deployment of more efficient, low-carbon solutions. Increasing investment in R&D is crucial for improving resource-use efficiency and reducing inputs. For example, by developing fertilizer alternatives, optimizing application methods to reduce emissions and runoff, and optimizing feed to lower methane emissions from livestock. Scaling up green technologies will require both financial incentives and targeted training for agricultural producers.

Thirdly, production systems must also be aligned with nutrition and sustainability goals. Shifting agricultural structures toward more nutritious and environmentally friendly food, and reducing losses across the supply chain—from production and processing to distribution and retail—can lower emissions while conserving resources. In parallel, promoting clean energy use in fertilizer production, food processing, transportation, and marketing can improve energy efficiency and reduce costs.

Finally, technology-and market-based incentive mechanisms are vital to enhance carbon sinks from land, land use, and forestry. Technologically, more efforts are needed to scale up ecological carbon sequestration solutions and develop region-specific conservation strategies for tillage and grassland protection. On the market side, China should continue to expand its carbon trading and green finance systems. LULUCF carbon sinks should be fully integrated into voluntary carbon markets, and the development of green financial instruments to support forest and grassland restoration should be encouraged. These efforts will enable carbon sequestration efforts, such as farmland conservation, afforestation, and grassland rehabilitation, to generate economic value. Market-based incentives can play a vital role in encouraging low-carbon land management practices, fostering both ecological and economic gains.

Reference

He, Y., Piao, S., Ciais, P. et al. Future land carbon removals in China consistent with national inventory. *Nat Commun* 2024, 15, 10426. https://doi.org/10.1038/s41467-024-54846-2

Huang A, Gupta A, Jiang H, et al. Phase Change-Mediated Capture of Carbon Dioxide from Air with a Molecular Triamine Network Solid. Journal of the American Chemical Society, 2025, 147(12): 10519-10529.

Banhazi T, Lehr H, Black J, et al. Precision Livestock Farming: An International Review of Scientific and Commercial Aspects. International Journal of Agricultural and Biological Engineering, 2012, 5(3): 1-9.

Brito L F, Bedere N, Douhard F, et al. Review: Genetic selection of high-yielding dairy cattle toward sustainable farming systems in a rapidly changing world. Animal, 2021, 15100292.

Richardson C, Amer P, Post M, et al. Breeding for sustainability: Development of an index to reduce greenhouse gas in dairy cattle. Animal, 2025: 101491.

De Haas Y, Veerkamp RF, De Jong G, et al. Selective breeding as a mitigation tool for methane emissions from dairy cattle. Animal, 2021: 100294.

FAO, 2023. Achieving SDG 2 without breaching the 1.5℃ threshold: A global roadmap, Part 1-How agrifood systems transformation through accelerated climate actions will help achieving food security and nutrition, today and tomorrow, In brief. Rome.

Gao Y, Cabrera Serrenho A. Greenhouse gas emissions from nitrogen fertilizers could be reduced by up to one-fifth of current levels by 2050 with combined interventions. Nature Food, 2023, 4: 170-178.

Gu B, Zhang X, Lam SK, et al. . Cost-effective mitigation of nitrogen pollution from global croplands. Nature, 2023, 613: 77-84.

Haque M. Dietary manipulation: a sustainable way to mitigate methane emissions from ruminants. Journal of Animal Science and Technology, 2018, 60(1): 15.

Hassanat F, Gervais R, Julien C, et al. Replacing alfalfa silage with corn silage in dairy cow diets: Effects on enteric methane production, ruminal fermentation, digestion, N balance, and milk production. Journal of Dairy Science, 2013, 96(7): 4553-4567.

Hristov A N, et al. An inhibitor persistently decreased enteric methane emission from dairy cows with no negative effect on milk production. Proceedings of the National Academy of Sciences, 2015, 112(34): 10663-10668.

Khanna N, Lin J, Liu X, et al. An assessment of China's methane mitigation potential and costs and uncertainties through 2060. Nature Communications, 2024, 15: 9694.

Liu Z, Deng Z, Davis S J, et al. Monitoring global carbon emissions in 2021. Nature Reviews Earth & Environment, 2022, 3: 217-219.

Macome F M, Pellikaan W F, Hendriks W H, et al. In vitro gas and methane production in rumen fluid from dairy cows fed grass silages differing in plant maturity, compared to in vivo data. Journal of Animal Physiology and Animal Nutrition, 2018, 102(4): 843-852.

Michael A. Clark, et al. Global food system emissions could preclude achieving the 1.5° and 2℃ climate change targets. Science, 2020, 370(6516): 705-708.

Neethirajan S. The role of sensors, big data and machine learning in modern animal farming. Sensing and Bio-Sensing Research, 2020, 29 : 100367.

Roe S, Streck C, Beach R, et al. Land-based measures to mitigate climate change: Potential and feasibility by country. Global Change Biology, 2021, 27: 6025-6058

Springmann M, Clark M, Mason-D'Croz D, et al. Op tions for keeping the food system within environmental limits. Nature, 2018, 562: 519-525.

Tang K, He C, Ma C, et al. Does carbon farming provide a cost-effective option to mitigate GHG emissions? Evidence from China. Australasian Journal of Agricultural and Resource Economics, 2019, 63(3): 575-592.

van Zelst V T M, Dijkstra J T, van Wesenbeeck B K, et al. Cutting the costs of coastal protection by integrating vegetation in flood defences. Nature Communications, 2021, 12: 6533.

Wang Y, Zhu Z, Dong H, et al. Mitigation potential of methane emissions in China's livestock sector can reach one-third by 2030 at low cost. Nature Food, 2024, 5: 603-614.

Xie Z, Han B, Sun Y, et al. Green carbon science for carbon neutrality. National Science Review, 2023, 10 (9): nwad225.

Shi X R, Zheng Y X, Lei Y, et al. Air quality benefits of achieving carbon neutrality in China. Science of The Total Environment, 2021, 795: 148784.

Hu Y C, Ren S G, Wang Y J, et al. Can carbon emission trading scheme achieve energy conservation and emission reduction? Evidence from the industrial sector in China. Energy Economics, 2020, 85: 104590.

Zhang Y, Song G, Lal N K, et al. TurboID-based proximity labeling reveals that UBR7 is a regulator of N NLR immune receptor-mediated immunity. Nature Communications, 2019, 10: 3252.

Fu X, Zhang YX, Wang XJ. Projection of forest biomass carbon pools and sequestration potential in China before 2060. Scientia Silvae Sinicae, 2022, 58(2): 32-41.

Fang JY, Geng XQ, Zhao X, et al. How much of China's grassland is there?. Chinese Science Bulletin, 2018, 63(17): 1731-1739.

Hu GZ, Ganjurjav H, Li MJ, et al. Modeling soil carbon sequestration under grassland ecological management in China using IPCC inventory methodology. Climate Change Research, 2023, 19(3): 371-380.

Fang JY, Yu GR, Ren XB, et al. Carbon sequestration effects of China's terrestrial ecosystems: Research progress of the carbon sequestration task force under the CAS strategic priority research program on climate change. Bulletin of Chinese Academy of Sciences, 2015, 30(6): 848-857+875.

He, Y., Piao, S., Ciais, P. et al. Future land carbon removals in China consistent with national inventory. Nat Commun 15, 10426 (2024). https://doi.org/10.1038/s41467-024-54846-2

Hu C, Li YY, Xue CX, et al. Spatiotemporal patterns of net carbon sink under conservation tillage in China. Journal of Natural Resources, 2022, 37(5): 1164-1182.

Li Y, Zhao XR, Li GT, et al. Grazing effects on soil microbial biomass phosphorus and phosphatase activity across topographic units in Inner Mongolia steppe. Acta Ecologica Sinica, 2022, 42(10): 4137-4149.

Liang YW, Huang Y, Zhou W, et al. Responses and feedbacks of China's agricultural non-point source pollution to global change. Chinese Journal of Applied Ecology, 2011, 22(11): 2925-2932.

Liu ZL, Yu WT. Research advances in organic carbon within soil aggregates. Chinese Journal of Eco-Agriculture, 2011, 19(2): 447-455.

Liu YC, Yu GR, Wang QF, et al. Meta-analysis of mature forest biomass reveals China's forest carbon capacity and sequestration potential. Scientia Sinica Vitae, 2015, 45(2): 210-222.

Lu F., H. Hu, W. Sun, J. Zhu, G. Liu, W. Zhou, Q. Zhang, P. Shi, X. Liu, X. Wu, L. Zhang, X. Wei, L. Dai, K. Zhang, Y. Sun, S. Xue, W. Zhang, D. Xiong, L. Deng, B. Liu, L. Zhou, C. Zhang, X. Zheng, J. Cao, Y. Huang, N. He, G. Zhou, Y. Bai, Z. Xie, Z. Tang, B. Wu, J. Fang, G. Liu, & G. Yu, Effects of national ecological restoration projects on carbon sequestration in China from 2001 to 2010, Proc. Natl. Acad. Sci. U.S.A. 2018, 115 (16) 4039-4044, https://doi.org/10.1073/pnas.1700294115

Qiao SY. Research and Application of Low-Protein Diets for Swine. Beijing: China Agriculture Press, 2000.

Qiao SY, Zhou JY, Li SK, et al. Low-protein and low-soybean-meal diversified diets as key technology for saving grain and improving efficiency in pig production. Chinese Journal of Animal Nutrition, 2024, 36(6): 3401-3412.

Wang B, Yu LJ, Fu XF, et al. Research progress in reducing methane emissions from sheep through selective breeding. Grass-Feeding Livestock, 2019, (3): 1-5.

Wang Q. Challenges and pathways for China-Kazakhstan green energy cooperation under carbon neutrality. Russian, Central Asian & East European Market, 2023, (1): 70-85+126.

Xu RF, Zhao MJ, Gao JZ. Measurement and spatiotemporal differentiation of agricultural grey water footprint in China. Chinese Journal of Agricultural Resources and Regional Planning, 2023, 44(10): 52-66.

Zhang HL, Chang Y, Lou WQ, et al. Novel traits in dairy cattle breeding. Acta Veterinaria et Zootechnica Sinica, 2021, 52(10): 2687-2697.

Zhang YM, Sheng FF, Chen ZG, et al. Potential impacts of China-US trade agreement on global soybean industry: A partial equilibrium analysis with bilateral trade module. Journal of Agrotechnical Economics, 2021, (4): 4-16.

Zhu SQ, Fu D, Zhang J, et al. Research advances in biomass and productivity of China's typical forest types. Acta Ecologica Sinica, 2003, 23(11): 2361-2370.

Zou JW, Huang Y, Zhou W, et al. Response and feedback of agricultural non-point source pollution to global change in China. Chinese Journal of Applied Ecology, 2011, 22(11): 2925-2932.

Acknowledgments

This report was supported by grants from the following funding agencies: the International (Regional) Cooperation and Exchange Program of the National Natural Science Foundation of China (NSFC Grant No. 72061147002), NSFC General Programs (Grant Nos. 72373145, 72373143, 72274196), NSFC Young Scientists Fund (Grant Nos. 72103188, 72003089, 72403234, 71904189), the Major Program of National Social Science Foundation of China (Grant No. 22&ZD085), the Planning Fund for Humanities and Social Sciences Research of the Ministry of Education (Grant No. 23YJA790087), the Humanities and Social Sciences Fund of the Ministry of Education (Grant No. 24YJCZH374), and the Beijing Social Science Foundation (Grant No. 24JCB048). Additional support was provided by the Low-Carbon Transition Capacity Building Initiative for Agricultural and Food Systems, the National Innovation Team Program of China Agricultural University, the China Scholarship Council, the "2115 Talent Development Program" of China Agricultural University, and the Chinese Universities Scientific Fund (2025TC031).

We gratefully acknowledge the institutional support provided by the Beijing Representative Office of the Environmental Defense Fund, World Resources Institute (WRI), Food and Land Use Coalition (FOLU), GFI Consulting (Shanghai) Co., Ltd., and Tianren Culture (Hong Kong) Limited.

Special recognition is extended to the following distinguished experts for their invaluable contributions and professional guidance: Dr. Qian Keming (Research Fellow, Chinese Academy of Agricultural Sciences; former Vice Minister, Ministry of Commerce), Prof. Zhang Fusuo (Academician of the Chinese Academy of Engineering; Professor, China Agricultural University), Dr. Chen Mengshan (Chairman, National Food and Nutrition Advisory Committee), Dr. Wang Ren (Senior Advisor for International Cooperation, Agricultural Genomics Institute at Shenzhen, Chinese Academy of Agricultural Sciences), Dr. Zhao Wenhua (Chief Expert, National Institute for Nutrition and Health, Chinese Center for Disease Control and Prevention), Prof. Hu Xiangdong (Director, Institute of Agricultural Economics and Development, Chinese Academy of Agricultural Sciences), Dr. Gao Ji (Director for Energy and Nature, Environmental Defense Fund), Dr. Qiu Ying (Senior Director for People and Nature, Environmental Defense Fund), Dr. Sun Fang (Senior Manager for Climate-Smart Agriculture, Environmental Defense Fund), and Mr. Yao Jikun (Director of International Public Affairs and Social Impact, Yara International).

Finally, we express our deepest gratitude to all research staff at the Academy of Global Food Economics and Policy for their dedicated efforts and scholarly contributions to this research endeavor.