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Agricultural Exports and Carbon Emissions in China: A Literature Review of Theoretical Foundations, Mechanisms, and Research Gaps

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ABSTRACT

Agriculture is a crucial sector for economic growth in emerging nations and a significant contributor to global carbon emissions. China, a leading agricultural producer and trader, has proactively responded to the Intergovernmental Panel on Climate Change's (IPCC) climate action appeal by proposing "Dual Carbon" targets as a national strategy. This review explores existing literature on the impact of agricultural exports on agricultural carbon emissions in China, focusing on energy consumption as a mediating factor, and environmental governance and R&D investment as moderating variables. It introduces a conceptual framework to understand how trade-led agricultural growth interacts with energy use and governance capacity, offering policy implications for balancing agricultural development with environmental goals. The review identifies research gaps and supports strategies to reduce emissions, strengthen governance, and promote innovation in pursuit of China's climate targets.

Keywords: Agricultural Exports, Agricultural Carbon Emissions, Energy Efficiency, Low-carbon Economy, Clean Energy Technology

INTRODUCTION

Carbon Emissions (CE) from agricultural production activities constitute 23% of the global total, positioning agriculture as the second-largest carbon-emitting sector worldwide. Agriculture undeniably plays a key role in global climate change (Liu and Yang, 2021). In China, Agricultural Carbon Emissions (ACE) account for 17% of the nation's total CE—above the global average of 13.5%—making China a significant contributor to global ACE (Cui et al., 2021; Du et al., 2023). Achieving economic growth while balancing agricultural exports and environmental protection has become a vital challenge, and low-carbon development has emerged as a cornerstone of China's policy.

CO_2 constitutes approximately 76% of total GHG emissions and continues to rise rapidly, contributing to record-breaking global temperatures nearing 1.5°C above pre-industrial levels (IPCC, 2022; Copernicus Climate Change Service, 2024). These trends, accompanied by melting glaciers, rising seas, and extreme weather, underscore the urgency of mitigation (IPCC, 2022). International efforts include the UNFCCC (1992), Kyoto Protocol (1997), and Paris Agreement (2015), under which nations committed to limit warming to within 1.5–2°C (Bao et al., 2023; Ou et al., 2021) (Table 1).

China, as the largest developing nation, faces immense pressure to reduce emissions. It contributes 30% of global CO_2 (Zheng et al., 2020) and is the foremost food producer and exporter (OECD & FAO, 2023). Agriculture, the second-largest emitting sector, produces 11–12% of national ACE, largely from fertiliser use, mechanisation, and biomass burning (Guo et al., 2022).

Table 1. Key Climate Change Conferences and Agreements

Year	Location	Conference Name	Law/Agreement	Core Objective	Key Outcomes
1863	United Kingdom (UK)	—	Alkali Act	Industrial pollution control	First environmental law targeting chemical industry emissions
1992	Rio, Brazil	Rio Earth Summit	UNFCCC	Establish a global climate framework	Developed nations agreed to take the lead in reducing emissions
1997	Kyoto, Japan	COP3	Kyoto Protocol	Legally binding reduction targets	Developed nations committed to reducing emissions; U.S. later withdrew
2012	Doha, Qatar	COP18	Kyoto Protocol Doha Amendment	Extend Kyoto Protocol	Commitment period extended to 2020, but major economies did not support
2015	Paris, France	COP21	Paris Agreement	Global temperature control (1.5-2°C)	All nations committed to emissions reductions via Nationally Determined Contributions (NDCs)
2021	Glasgow, UK	COP26	—	Strengthen climate commitments	Countries revised NDCs, pledged coal phase-out, and addressed methane reduction

Note: COP = Conference of the Parties under the UNFCCC (United Nations Framework Convention on Climate Change).
Source: Alkali Act (1863); UNFCCC (1992, 1997, 2012, 2015); UK COP26 Presidency (2021). For full references, see the reference list.

Excessive fertiliser and pesticide application far exceed global averages, intensifying environmental costs (Wu et al., 2018; Jin et al., 2024). China announced its "Dual Carbon" goal at the United Nations in 2020, pledging to peak carbon emissions by 2030 and reach neutrality by 2060 (Mahmood et al., 2023). Yet progress during the 14th Five-Year Plan has lagged (Zhu et al., 2024). Agriculture remains central to both economic growth and emission reduction, highlighting the importance of sustainable practices (Delgado et al., 2020). Strengthening management is vital for balancing food security with low-carbon development (Van et al., 2021). While most existing studies emphasise scale, composition, and technique effects (Copeland & Taylor, 2004), they often ignore cumulative impacts and focus mainly on industrial exports. Few have systematically addressed agriculture, especially in emerging economies. In sum, existing research remains fragmented, often overlooking mediating and moderating mechanisms, and insufficiently covering agriculture. This paper highlights the main research gaps in the trade–environment studies, with particular emphasis on agricultural carbon emissions.

This research investigates how China's agricultural exports influence ACE, incorporating energy consumption as a mediating variable and environmental governance and Research and Development (R&D) investment as moderating variables. The Pollution Haven Hypothesis (PHH) serves as the primary theoretical lens, suggesting that lax environmental regulation may attract pollution-intensive industries, increasing emissions via trade (Copeland & Taylor, 1994). The Energy-Environment Transmission Mechanism (EMM) explains the indirect pathway from agricultural exports to emissions through energy-intensive production (Khan et al., 2021; Edoja et al., 2024). The Environmental Governance Theory (EGT) and Green Innovation Theory underpin the moderating roles of governance capacity and technological innovation (Chen et al., 2022; Karplus et al., 2021). The Environmental Kuznets Curve (EKC) provides a control framework to account for the nonlinear impact of economic development on environmental outcomes (Grossman & Krueger, 1991; Panayotou, 1993; Li et al., 2024). By reviewing these theoretical foundations, this paper addresses underexplored mechanisms in the trade–environment literature—particularly within agriculture—and highlights literature gaps in understanding the complex linkages between trade, emissions, and governance in developing countries like China.

THEORETICAL FOUNDATIONS OF THE TRADE–ENVIRONMENT NEXUS

This section examines academic literature regarding how economic and trade activities influence environmental outcomes. By reviewing theoretical and empirical studies, this section explains mechanisms through which trade affects the environment and discusses its favourable and unfavourable effects. To clarify these mechanisms, the study integrates the Pollution Haven Hypothesis (PHH), Environmental Governance Theory (EGT), Green Innovation Theory, and the Environmental Kuznets Curve (EKC) hypothesis to explain the direct, mediating, and moderating effects of agricultural exports on Agricultural Carbon Emissions (ACE). The EKC framework also controls for the nonlinear effect of economic growth on emissions.

Introduction to the Trade–Environment Nexus

Since the 1870s, scholars have recognised that economic activity imposes long-term pressure on environmental systems. *The Limits to Growth* (Meadows et al., 1972) examines how industrial expansion contributes to environmental degradation and highlighted the urgent need for sustainable development frameworks. Similarly, *The Theory of Environmental Policy* (Baumol & Oates, 1988) argued that economic growth leads to environmental externalities, thus validating the use of corrective tools such as pollution taxes. These foundational works paved the way for later research on the trade-environment nexus.

Building on these foundations, interest in the environmental effects of trade intensified with the acceleration of globalisation in the 1990s. While international trade fosters economic growth, it also generates significant environmental risks (Iyke-Ofoedu et al., 2024). The EKC hypothesis proposed an inverted U-shaped relationship between economic development and environmental degradation (Grossman & Krueger, 1991). This framework serves as a control perspective in this study, helping to isolate environmental impacts of trade from those of economic growth.

Copeland and Taylor (1994) proposed the PHH, arguing that firms in countries with strict environmental laws may relocate pollution-intensive industries to developing countries with weaker regulations. This mechanism contributes to transnational pollution transfer and ecological harm (Frank, 1997). In response, policy responses such as the UN Earth Summit (1992), the WTO Committee on Trade and Environment (1993), and international agreements like the Kyoto Protocol (1997) and Paris Agreement (2015) sought to balance trade liberalisation with environmental protection (Bernasconi-Osterwalder et al., 2023).

Trade affects the environment through three main channels: scale, composition and technique effects (Copeland & Taylor, 2004). The scale effect increases emissions by expanding the overall level of production. The composition effect reflects structural shifts toward or away from more carbon-intensive sectors. The technique effect reduces emissions per unit of output through technological improvements. The combination of these effects determines the net environmental impact of trade. In agriculture, exports may amplify ACE through increased production (scale), a shift toward high-emission crops (composition), or efficiency gains that reduce emissions (technique) (Escobar et al., 2020). These mechanisms are strongly influenced by policy setting and environmental governance quality (Panayotou, 2003).

The environmental effect of trade is context-specific, depending on which mechanism dominates and the strength of environmental governance (Grossman & Krueger, 1991). Copeland and Taylor observed that countries with weaker environmental regulation may become pollution havens. In agriculture, this suggests that exports-driven production may exacerbate ACE in developing countries (Copeland, 2004; Copeland & Taylor, 1994).

Given the multidimensional nature of the trade–environment nexus, no single theory fully captures its complexity. This study adopts the PHH as the primary theoretical framework, supplemented by the EEM to explain mediating pathways, and by EGT and Green Innovation Theory to explore moderating effects. The EKC is included as a control structure to account for the nonlinear effects of economic development on emissions. The following section introduces the PHH in detail.

Pollution Haven Hypothesis and Direct Trade-Emission Link

Overview of Pollution Haven Hypothesis

Walter and Ugelow (1979) discovered that developed countries transferred pollution-intensive industries to nations with lax environmental standards-foundational to Pollution Haven Hypothesis (PHH). Copeland and

Taylor (1994) formalised the hypothesis within a general equilibrium model based on Heckscher-Ohlin (H-O) theory, later verifying it empirically (1995).

The theory posits that nations with string environmental standards diminish production and export of pollution-intensive goods, while those with laxer rules increase such production to attract investment. Higher compliance costs reduce competitiveness, prompting firms to relocate to countries with weaker regulation. These areas attract polluting industries, leading to environmental degradation and becoming "pollution havens". In contrast, developed countries enforce strict standards and protect ecosystems. Developing countries prioritise growth and tolerate pollution to attract investment. Agriculture reflects this pattern: exports increase energy use and CO_2 emissions, contributing to Agricultural Carbon Emissions (ACE). Trade liberalisation thus risks worsening ACE, especially where environmental controls are weak (Copeland & Taylor, 2004).

Empirical Evidence in Agricultural Sectors

When a country's economic development is at a low level, residents prioritise income over environmental quality. Countries may attract high-pollution industries to drive growth (Copeland & Taylor, 1994; Frank, 1997; Walter & Ugelow, 1979), becoming pollution haven. As income rises, they improve governance, upgrade technologies, and restructure industries (Bernasconi-Osterwalder et al., 2023; Panayotou, 2003).

This also applies to agriculture. Whether export make a region a pollution haven depends on government and enterprise action. Effective countermeasures and low-emission production help reduce ACE (Copeland & Taylor, 2004; Escobar et al., 2020; Iyke-Ofoedu et al., 2024).

Energy–Environment Transmission Mechanism (EEM)

The Energy–Environment Transmission Mechanism (EEM) explain how agricultural trade affects the environment, especially in developing countries (Edoja et al., 2024; Khan et al., 2021). Trade expansion increases production intensity, driving greater use of energy-intensive inputs such as machinery, fertilisers and irrigation systems. Agricultural exports modernise agriculture while increasing reliance on energy, significantly impacting carbon emissions. This trend reflects agricultural intensification, that is, increasing output per unit of land via energy inputs. In China, this model supports export-led growth, especially in resource-limited regions. The theoretical basis lies in the production intensity effect: trade-induced output growth increases energy input and emissions. This has been empirically confirmed in Regional Comprehensive Economic Partnership (RCEP) countries and sub-Saharan Africa (Jin et al., 2024; Yılmaz, 2023). Fossil fuel dependence, notably diesel and coal, strengthens this trade-emission link.

Recent studies in the context of China's trade liberalization suggest that fluctuations in energy markets, particularly oil prices, influence national carbon emissions through their effects on the energy mix and industrial outputs, forming a key transmission mechanism linking trade and the environment (Ullah et al., 2024). Therefore, this study introduces energy consumption as a mediating variable between agricultural exports and ACE, capturing one key transmission pathway of trade-induced emissions.

Environmental Governance as a Moderating Mechanism

Environmental Governance Theory (EGT) explores how governments and institutions manage environmental challenges through laws and regulations, policy enforcement, investment, and collaboration (Chen et al., 2022; Karplus et al., 2021). It emphasises that effective governance mitigates the negative effects of economic activities, promoting sustainable development (Karplus et al., 2021; Liu & Xie, 2020).

This study conceptualises environmental governance as a quantifiable variable, specifically government investment, reflecting the government's commitment to pollution control and sustainability. The variable moderates the relationship between agricultural exports and ACE, influencing the extent to which trade contributes to emissions (Huang & Wu, 2022; Liu & Xie, 2020). Higher investment can help offset the environmental cost of trade expansion (Chen et al., 2022; Huang & Wu, 2022).

Green Innovation and Research and Development Perspectives

Technological innovation, especially green innovation, is key to sustainable agricultural development and improved environmental quality (Chenghu et al., 2021). The Porter hypothesis suggests that sound environmental regulations stimulate innovation, enhancing efficiency and reducing environmental burdens (Porter & Van der Linde, 1995).

In agricultural trade, Research and Development (R&D) investment supports clean technologies such as precision irrigation, eco-friendly fertilisers, and energy-efficient machinery (Fernández et al., 2018). Regions with higher R&D investment adopt cleaner technologies and reduce emissions associated with export-oriented production (Fragkiadakis et al., 2020; Huang et al., 2021; Song et al., 2023).

This study introduces R&D investment as a moderating variable that shapes the strength of the relationship between agricultural exports and ACE (Yahya & Lee, 2022; Zhang et al., 2021). Higher R&D weakens this link by promoting low-carbon practices and enhancing energy efficiency, supporting green trade (Fernández et al., 2018; Zhang et al., 2021).

The Environmental Kuznets Curve Hypothesis

Kuznets (1955) proposed that income inequality follows an inverted U-curve with economic growth. Grossman and Krueger (1991) extended this to the environmental, forming the Environmental Kuznets Curve (EKC) hypothesis. Their analysis revealed that pollution first increases, then decreases as income rises. Shafik & Bandyopadhyay (1992) and Panayotou (1993) further enriched the framework. **Table 2 summarises** the evolution of the EKC hypothesis.

Table 2. Key Contributions to the Development of the EKC Hypothesis

Year	Researchers	Key contribution	Key variables	Mathematical model
1955	Simon Kuznets	Proposed Kuznets Curve (inverted U-shape between income inequality & economic growth)	Income Inequality, Income, Income2	$Inequality=a+\beta_1 Icome+\beta_2 Icome^2+$ ϵ
1991	Grossman & Krueger	First identified the inverted U-shape relationship between economic growth & pollution	Pollution & Economic Growth	N/A
1993	Panayotou	Formally introduced EKC, analysing per capita income & environmental quality	Per Capita Income & Income^2	$Environmental\ Impact=a+\beta_1 Icome$ ϵ
1995	Grossman & Krueger	Refined EKC model with GDP, forming standard framework for later studies	GDP, GDP^2, GDP^3	$a+\beta_1 GDP+\beta_2 GDP^2+\beta_3 GDP^3+$ ϵ
After 1995-Present	Various Scholars	Expanded EKC applications with environmental and economic indicators	Different pollutants, additional factors	$+\beta_2 GDP^2+ (\beta_3 GDP^3) +\gamma X+$ ϵ

The EKC suggests that early growth worsens pollution, but later improvements follow rising income, innovation, and governance. However, variations exist (U-shape, N-shape, linear), depending on pollutants, countries, and time (Mahmood et al., 2023; Stern et al., 2006). In China, EKC patterns vary by region and pollutant (Sui et al., 2021; Wu et al., 2024). In agriculture, carbon emissions may rise with export-led growth, but decline as clean technologies spread (Saghaian et al., 2022; Yang et al., 2023). This review uses EKC as a control structure to account for non-linear income-ACE effects, while Pollution Haven Hypothesis (PHH), Environmental Governance Theory (EGT), and green innovation remain the core theoretical lenses.

Agricultural Carbon Emissions: Concepts, Trends and Drivers

Agriculture is the principal industry and main food source for humanity, yet food production inevitably generates carbon emissions (Flammini et al., 2021). Agricultural Carbon Emissions (ACE) are essential emissions tied to human survival (IPCC, 2019) and a major part of production-related emissions (Bai et al., 2024), making ACE crucial to global climate goals (Friedlingstein et al., 2023). With China's growing agricultural output and exports (Ali et al., 2022), studying ACE is crucial to advancing sustainable agriculture (Guo et al., 2023), promoting green trade (Song et al., 2023), and achieving carbon neutrality (Chu et al., 2024).

Definitions and Measurement Frameworks

Agricultural output significantly affects global climate change, primarily through CO_2 emissions, which accounts for approximately 76% of global GHG emissions (Li et al., 2021; Friedlingstein et al., 2023; Singh, 2024). Agriculture contributes roughly 23% of global CO_2 emissions, making it the second-largest emitting sector (Flammini et al., 2021). In China, ACE constitutes around 17% of total national emissions and 11–12% of global ACE (Cui et al., 2021; Du et al., 2023; Kamyab et al., 2024). Under the Paris Agreement's climate targets, CO_2 reduction remains a primary objective, and China's carbon peak and neutrality goals are closely aligned with these commitments (Van Veelen, 2021). In the literature, ACE are generally defined as CO_2 emissions generated from activities including farming, forestry, animal husbandry, fishery, and irrigation. Estimations are typically based on methodologies outlined in the IPCC National GHG Inventory Guidelines to ensure international comparability (Wang et al., 2021). In China-specific studies, emissions data often incorporate localised emission factors that reflect difference in crop types, soil characteristics, and regional agricultural practices. These emissions assessments encompass a wide range of sub-sectors, such as agriculture, forestry, livestock, fishery, and water resource management, thereby providing a comprehensive picture of the agricultural carbon profile.

Empirical Evidence on Agricultural Carbon Emissions in China

Empirical studies on ACE drivers largely fall into two categories: decomposition and econometric models. The Logarithmic Mean Divisia Index (LMDI), predominantly utilised in manufacturing, has limited application in agriculture due to data challenges. While applied, it attributes emissions to industrial activity, structure, energy intensity, fuel mix, and emissions intensity (Dolge & Blumberga, 2021; Sui & Lv, 2021; Yang et al., 2022).

The second category includes econometric models such as Auto-regressive Distributed Lag (ARDL), the Stochastic Impacts by Regression on Population, Affluence, and Technology (STIRPAT) and Environmental Kuznets Curve (EKC). ARDL captures short- and long-term dynamics but is limited by its linear structure and time series requirements (Guo et al., 2023; Tanveer et al., 2024). The STIRPAT model explores impacts of population, affluence, and technology, showing that structural upgrades and mechanisation may reduce ACE, while affluence increases it (Mao, 2023; Huang et al., 2022). However, STIRPAT lacks capacity to capture nonlinear dynamics.

To address this, many studies use the Environmental Kuznets Curve (EKC) model alongside STIRPAT to explore nonlinearities (Mahmood et al., 2021; Peng & Zhan, 2021). EKC explains inverted U-shaped trends between growth and emissions across provinces. While not the main theory, this study adopts EKC as a control structure to account for nonlinearity in ACE–export linkages, complementing the PHH and EGT frameworks.

Main Drivers of Agricultural Carbon Emissions

Agricultural Production Practices

Energy consumption is a critical driver of ACE, particularly due to fossil fuel use in mechanised farming. Agricultural modernisation has increased machinery and irrigation usage, raising energy demand. and ACE. Studies show a strong correlation between agricultural energy use and ACE, especially in developing and some European countries (Flammini et al., 2021; Hercher-Pasteur et al., 2020; Sulewski & Wąs, 2024; Xu et al., 2021; Zhang et al., 2019). Mechanisation and irrigation systems further raise emissions in large-scale farms (Cui et al., 2021; Gao et al., 2021). Agricultural exports may intensify ACE by expanding production and energy input (Edoja et al., 2024; Jin et al., 2024; Khan et al., 2021).

Land Use Changes

Deforestation from agricultural expansion is a significant driver of carbon emissions and biodiversity loss (OECD & FAO, 2023)

Agricultural trade increases soil degradation, land conversion and releasing carbon emissions. In China, such impacts are mitigated by forest policies, but demand for imports (e.g., soybeans) indirectly influenced deforestation aboard, notably in Brazil (Kan et al., 2021; Sarathchandra et al., 2021). Land use changes, including deforestation and expansion of cultivated land, as well as the emergence of non-grain cropland expansion, significantly contributed to ACE (Daum et al., 2022; Li et al., 2024).

Fertiliser and Pesticide Use

To boost yield and quality, agriculture often relies heavily on fertilisers and pesticides (Gao et al., 2021; Wu et al., 2018). Excessive use increase nitrogen oxide emissions and pollutes soil and water (Li et al., 2021; Guo et al., 2022). Their production is energy-intensive and releases large amount of carbon emissions (Hercher-Pasteur et al., 2020; Zhang et al., 2021). Long-term overuse also depletes soil carbon storage, indirectly increasing emissions (Benzerrouk et al., 2021). Under China's production-oriented model, raising trade and output further drive the use of fertilisers and pesticides, contributing to ACE (Jin et al., 2024; Meng et al., 2022).

Technological Innovation

Technological innovation in green agriculture, energy-saving equipment, and smart farming is key to reducing ACE. Research and Development (R&D) investment drives improvements in machinery, fertilisers, irrigation systems and overall efficiency (Fernández et al., 2018; Iyke-Ofoedu et al., 2024; Song et al., 2023). These improvements enhance productivity and enable low-carbon technologies, significantly reducing ACE intensity (Flammini et al., 2021; Fragkiadakis et al., 2020). In China, such progress has lowered the carbon intensity of agricultural export (Song et al., 2023). Technological advancement may also moderate the impact of exports on ACE (Xu et al., 2020; Zhang, 2023).

Institutional and Policy Factors

Institutional and policy factors influence ACE through carbon targets, production regulations, and environmental governance (Du et al., 2023). Environmental governance reflects governmental commitment to emission reduction, playing a crucial role in green agricultural development. Effective governance promotes green investment, reduces resource waste, supports low-carbon technology adoption, and enables coordinated agriculture-environment progress, thereby reducing ACE (Ji et al., 2024).

Studies show governance capacity may moderate the link between exports and ACE (Lu & Dai, 2023). Export expansion may increase resource use and emissions, but strong governance can mitigate such impacts. Conversely, weak governance can amplify environmental damage (Huang & Wu, 2022). However, most studies focused on general drivers like R&D or governance, with limited focus on their moderating effects. Exploring institutional roles in carbon reduction remains crucial and provides theoretical support for the analysis ahead.

In sum, ACE is shaped by interacting factors including production practices, land use, fertiliser and pesticide use, technology, and policy. Understanding these drivers is essential for mitigating ACE and advancing sustainable agriculture and lays a solid foundation for further thematic discussion in the following sections.

Agricultural Trade and Environmental Outcomes

As global trade liberalisation progresses, agricultural exports increasingly shape national economies, especially in emerging nations. While such exports promote economic growth and rural development, they also generate environmental externalities and deteriorate ecosystems. It is therefore essential to examine their environmental impacts. This section reviews both positive and negative environmental effects of agricultural exports.

Positive and Negative Environmental Effects of Agricultural Exports

Negative Effects

With globalisation, agricultural trade has become an integral part of global commerce and a policy priority for economic growth in developing countries. However, agriculture—especially livestock and intensive fertiliser use—is a major source of carbon emissions, contributing significantly to environmental pollution and climate change (Song et al., 2023). Because of lax environmental control, agricultural exports in developing nations often increase emissions (Saghaian et al., 2022). While many studies examine trade and carbon emissions generally, fewer focus on the environmental effects of agricultural exports, particularly in China. For instance, Brazilian soybean exports have driven land-use change, deforestation, and processing emissions (Escobar et al., 2020). A study of 43 developing countries also confirmed increasing greenhouse gas emissions linked to agricultural export (Saghaian et al., 2022). In China, export growth in areas like the Anhui Free Trade Zone has worsened ACE (Li & Choi, 2022).

Export-driven expansion may weaken environmental regulations, resource overuse and raise energy demand. Cross-border logistics, especially high-energy-consuming cold-chain and long-distance shipping, further add to emissions (Balogh & Jámbor, 2020; Meng et al., 2022).

Positive Effects

Most literature focuses on the negative impact of export trade on carbon emissions (CE), while fewer studies affirm the positive environmental implications of agricultural exports. A study involving 43 developing and 23 developed nations revealed that agricultural exports raise GHG emissions in developing countries but diminish them in developed countries, reflecting regional variations in trade's on environmental effects (Saghaian et al., 2022). In China, research across provinces indicates that agricultural trade can reduce ACE, particularly in regions with high agricultural industrialisation, agglomeration, flat terrain, and mid-west or non-grain areas. This is mainly due to the progress of agricultural technology and structural optimisation of the sector (Zhang, 2023; Zhang et al., 2024). In addition, emission heterogeneity has been confirmed: while trade lowers CO_2 emissions, it may increase emissions of other GHGs, such as NO_2 and CH_4 (Yahya & Lee, 2022).

Evidence from China's Agricultural Trade-Emissions Studies

Overview: Agricultural Exports and Environmental Pressures

The expansion of international trade brings complex environmental consequences. Trade liberalisation can exacerbate development imbalances, especially in developing countries where economic growth is often prioritised over environmental protection, leading to resource overexploitation and environmental degradation, or the relocation of pollution-intensive industries to less regulated regions (Chen et al., 2023; Duan et al., 2021; Saghaian et al., 2022).

According to the Organisation for Economic Cooperation and Development (OECD) and Food and Agriculture Organisation (FAO), agriculture remains central to global trade, with agricultural trade reaching $1.7 trillion, about 10% of global trade (OECD & FAO, 2023). It plays an important role in food security, employment, economic growth, and rural development-particularly for developing countries-but also generates significant environmental costs. Agricultural exports lead to deforestation, overuse of land and water, biodiversity loss, and increased carbon emissions, thereby changing ecosystems, and accelerating environmental degradation (Balogh & Jámbor, 2020; Flammini et al., 2021; Hong et al., 2022; Zhao et al., 2022). Therefore, developing sustainable agricultural practices is critical to mitigate these impacts.

Such environmental challenges have received broad academic attention. According to the Pollution Haven Hypothesis (PHH), countries with lax regulations may attract pollution-intensive industries (Duan et al., 2021; Lu & Dai, 2023). As a developing country with increasing trade openness, China's agricultural exports have expanded with economic growth and growing international demand. The environmental impacts of China's agricultural trade cannot be ignored, especially due to carbon-intensive production and energy dependence (Chen et al., 2023; Guo et al., 2022; Li & Zhang, 2024; Meng et al., 2022; Song et al., 2023). Effective policies and sustainable practices are urgently needed to address these issues.

Agricultural Exports and Carbon Emissions

Agriculture is a primary contributor of CE, particularly through land cultivation, livestock farming, and the intensive use of chemical fertilisers. According to the IPCC, emissions from agriculture, deforestation, and other land uses constitute over 20% of global CE (IPCC, 2019), underscoring the critical impact of agricultural practices on the climate system. In this context, understanding the relationship between agricultural trade and CE is crucial.

CE generated during the production and trade of agricultural goods influences both China's domestic ACE and contributes to global climate change (Meng et al., 2022; Song et al., 2023). China's agricultural trade increases global CE through both domestic production and the international transport of goods. For instance, the import of oil crops such as soybeans and rapeseed from countries like the United States, Brazil, and ASEAN shifts part of China's CE to these exporting nations (Song et al., 2023).

Conversely, China's agricultural export raise domestic CE due to intensive farming, high energy use, and extensive fertilisers application (Guo et al., 2022; Meng et al., 2022). Moreover, raw materials in China's exports often originate from other developing nations, transferring part of the CE burden via global supply chains (Zhao et al., 2022).

While agricultural trade provides economic benefits, it brings complex environmental costs, including deforestation, land alteration, water scarcity, biodiversity loss, and rising GHG emissions (Guo et al., 2022; Hong et al., 2022). Addressing these concerns requires sustainable farming practices and stronger environmental governance. Integrating environmental considerations into trade policy is crucial for aligning China's agricultural growth with ecological sustainability (Meng et al., 2022).

Mechanisms Linking Exports to Emissions

Trade impacts the environment through three key mechanisms: scale, composition, and technique effects. The scale effect describes how increased trade openness expands economic activities, leading to greater resource consumption and pollution in the absence of improved production efficiency and environmental governance. This often results in environmental degradation, making the scale effect initially negative (Grossman and Krueger, 1991). However, as trade boosts GDP and income levels, societies begin demanding better environmental quality, and governments have more resources for environmental protection. Over time, the scale effect may turn positive, depending on development stages and governance capacity (Duan et al., 2021).

The composition effect arises from trade-induced changes in industrial structure. Based on comparative advantage, countries tend to specialise in sectors where they are most efficient. If the shift favours clean industries, environmental outcomes improve; if it favours resource- or pollution-intensive industries, outcomes is negative (Grossman & Krueger, 1991). Trade also affects prices and resource allocation, shaping production and consumption patterns. For instance, rising agricultural prices may incentivise producers to adopt resource-intensive practices, thereby negatively affecting the environment (Yan et al., 2021). Moreover, weak regulations in developing countries can attract pollution-intensive industries (Chen et al., 2023; Copeland & Taylor, 2004).

The technique effect reflects how trade promotes access to cleaner technologies, innovation, and improved efficiency. Exposure to international markets and competition encourages green technology adoption, especially in developing countries (Wang et al., 2023). Technology spillovers from imports can enhance domestic environmental practices, although, outdated technologies may also be transferred (Grossman & Krueger, 1991).

These three effects, scale, composition, and technique, interact to determine the overall environmental impact of trade. In agricultural exports, production expansion often increased energy consumption, making energy use an important mediating pathway linking trade to ACE (Guo et al., 2022; Meng et al., 2022; Song et al., 2023)

Integrating Mediating and Moderating Mechanisms

Based on the theoretical understanding of the relationship between agricultural exports and Agricultural Carbon Emissions (ACE), this section further introduces mediating and moderating variables to explore specific transmission pathways and conditions influencing this relationship. Specifically, energy consumption is proposed as a mediating variable to reveal how agricultural export expansion may exacerbate ACE, particularly in developing countries with weaker environmental governance (Saghaian et al., 2022). Also, environmental governance and R&D investment are incorporated as moderating variables to examine how institutional capacity and technological progress affect the strength and direction of this relationship. These variables help clarify under what conditions agricultural exports are more likely to contribute to higher emissions and when their impact may be mitigated. This integrative approach enables a more systematic understanding of the indirect and conditional pathways through which agricultural trade affects environmental outcomes and provides a foundation for the conceptual framework and subsequent analysis.

Energy Consumption as a Mediating Variable

Energy consumption refers to the total amount of energy consumed in agricultural production activities, including fertiliser production, mechanised operations, and irrigation (Hercher-Pasteur et al., 2020; Sulewski & Wąs, 2024). Agriculture, highly dependent on energy, is one of the most energy-intensive industries (Hercher-Pasteur et al., 2020). With the acceleration of agricultural modernisation and the widespread use of mechanised production and irrigation systems, energy consumption has increased significantly (Sulewski & Wąs, 2024). According to the energy–environment transmission mechanism, energy consumption is conceptualised as an important mediating variable that connects agricultural exports to carbon emissions. This mechanism is grounded in the energy–environment transmission theory, which emphasises that trade-driven agricultural intensification results in heightened energy input and consequently worsens environmental effects, especially carbon emissions (Edoja et al., 2024; Khan et al., 2021).

Agricultural exports, as an important economic driver, not only promote economic growth and agricultural modernisation but have also been shown to increase agricultural intensification. This intensification leads to higher consumption of inputs such as fertilisers and pesticides, thereby significantly raising energy consumption levels (Khan et al., 2021). Energy consumption has been demonstrated to be closely related to Agricultural Carbon Emissions (ACE); agricultural production activities release large amounts of greenhouse gases through the combustion of fossil fuels such as coal, oil, and natural gas (Xu et al., 2021; Zhang et al., 2019). This impact is particularly evident in developing countries and Europe (Flammini et al., 2021).

An increasing body of research recognises that in the context of agricultural product exports, energy consumption serves as a critical mediator linking trade expansion to carbon emissions. Prior studies show that export expansion tends to intensify production and input use, leading to increased energy consumption and exacerbating carbon emissions (Jin et al., 2024; Khan et al., 2021). A study based on 105 countries found that trade liberalisation significantly increases energy consumption in developing countries, thereby indirectly driving up carbon emissions (Zandi, 2019). A similar mechanism was also demonstrated in 30 Sub-Saharan Africa countries (Yılmaz, 2023). In Nigeria, studies emphasised that agricultural trade and energy consumption both have significant positive effects on carbon emissions, with energy use serving as a transmission channel between trade and environmental degradation (Edoja et al., 2024). This mediating role is also confirmed in the studies of Regional Comprehensive Economic Partnership (RCEP) member countries and in Pakistan (Jin et al., 2024; Khan et al., 2021).

Overall, the mediating role of energy consumption is widely acknowledged. Therefore, it is theoretically and empirically justified to propose that energy consumption mediates the relationship between agricultural exports and ACE (Guo et al., 2022).

Environmental Governance as a Moderating Variable

The fundamental problem of environmental pollution is that the environment is a public good with negative externalities. When the market fails to address environmental contamination, governmental intervention is necessary. Environmental governance, as a means of environmental constraints, can effectively reduce environmental pollution and carbon emissions (Brock & Taylor, 2010). This variable is grounded in

Environmental Governance Theory (EGT), which emphasises the role of institutions, regulations, and policy implementation in mitigating environmental impacts (Chen et al., 2022; Karplus et al., 2021).

In China, environmental issues pose a major challenge. As a leading economic power and major pollutant emitter, China faces a dilemma between conservation and development. The concept of environmental governance emerged in the 1970s, and evolved from basic regulations to broader notions such as green development (Karplus et al., 2021). Investment in pollution control reflects government commitment and serves as a key measure in environmental governance. Scholars use government spending on pollution control as a proxy for governance strength (Chen et al., 2022).

According to Environmental Governance Theory (EGT) and the Porter Hypothesis, governance can moderate the trade–emissions relationship by shaping regulatory influence economic activity. The Pollution Haven Hypothesis (PPH) suggests that stricter governance raises costs, discouraging pollution-intensive trade (Walter & Ugelow, 1979). In contrast, the Porter Hypothesis argues that strong governance stimulate innovation and competitiveness (Porter & Van der Linde, 1995). For instance, United States carbon taxes reduce agricultural exports like soybeans (Dumortier & Elobeid, 2021), while in China, governance can reduce ACE or promote clean upgrades (Chen et al., 2023; Liu & Xie, 2020).

Governance impact varies by region. Stricter governance can reduce ACE in developed eastern regions but may hinder development in less-developed western regions (Lu & Dai, 2023). Therefore, selecting the appropriate level of environmental regulation is essential when designing trade and environmental policies (Lu & Dai, 2023).

Overall, integrating environmental governance with low-carbon principles is essential for China's sustainable development (Chen, 2023; Shang & Xu, 2022)

Research and Development Investment as a Moderating Variable

Research and Development (R&D) Expenditure refers to the total spending by governments, enterprises, and research institutions on basic research, applied research, and experimental development. Its objectives include enhancing production efficiency, promoting technological advancement, and improving resource use and environmental sustainability (Aghion et al., 2009; Fernández et al., 2018). R&D investment is a key driver of technological innovation and sustainable development, grounded in Green Innovation Theory, which connects technological progress to productivity and environmental outcomes (Fernández et al., 2018). It is typically measured as a percentage of regional GDP, allowing for consistent comparison across regions and time periods by accounting for economic scale differences (Mairesse & Mohnen, 2010).

The moderating role of R&D investment is supported by Green Innovation Theory and the Porter Hypothesis, which suggest that technological upgrading mitigates environmental damage from economic activity. In the context of agricultural trade, R&D investment may weaken the link between export expansion and ACE by enabling more efficient, low-emission practices. Conversely, regions with insufficient R&D investment may remain reliant on energy-intensive traditional production, exacerbating carbon emissions (Jin et al., 2024; Khan et al., 2021).

Many studies indicate that technological innovation contributes to carbon reduction and improved environmental quality (Huang et al., 2021). The Porter hypothesis posits that stringent environmental regulations can drive innovation and productivity gains. Increased R&D investment encourages clean energy use, technological upgrading, and emission reduction strategies among exporters (Fernández et al., 2018; Fragkiadakis et al., 2020).

Empirical evidence confirms that advances in environmental technology and R&D contribute to reducing carbon emissions and their inequality, underscoring their importance in moderating trade – environment outcomes (Bergougui et al., 2024). Empirical research on China's export carbon intensity suggests that R&D investment has helped reduce emission by promoting technological transformation (Song et al., 2023; Yahya & Lee, 2022; Zhang et al., 2021).

Therefore, R&D investment is introduced as a moderating variable in the link between agricultural exports and ACE. This allows for a comprehensive understanding of how regional innovation capability shapes the environmental impacts of trade expansion.

CONCEPTUAL FRAMEWORK

Based on the theoretical foundations and empirical literature reviewed above, this study constructs a conceptual framework for analysing the impact of agricultural exports on China's Agricultural Carbon Emissions (ACE). The framework incorporates five theoretical perspectives: trade-environment relationship theory, the Pollution Haven Hypothesis (PHH), the energy-environment transmission mechanism, Environmental Governance Theory (EGT), and green innovation theory derived from the Porter hypothesis. Additionally, the

Environmental Kuznets Curve (EKC) is employed as a control structure to address the non-linear relationship between economic development and environmental degradation (Walter & Ugelow, 1979; Edoja et al., 2024; Chen et al., 2022; Porter & Van der Linde, 1995; Wang & Lv, 2022).

As shown in **Figure 5.1**, agricultural exports serve as the independent variable, and ACE is the dependent variable. Energy consumption mediates the impact of export-driven production intensification on emissions (Xu et al., 2021). Environmental governance and R&D investment are introduced as moderating variables, representing institutional strength and technological capacity, respectively (Lu & Dai, 2023; Yahya & Lee, 2022).

The framework integrates mediating and moderating effects and embeds the EKC to explain trade-environment linkage in agriculture more systematically (Trofimov, 2022). While control variables such as energy structure, agricultural mechanisation, fertiliser use, and foreign direct investment are not central to the theoretical framework and thus excluded from the diagram, they are frequently considered in empirical studies to address omitted variables bias and enhance explanatory robustness (Cui et al., 2021; Guo et al., 2023).

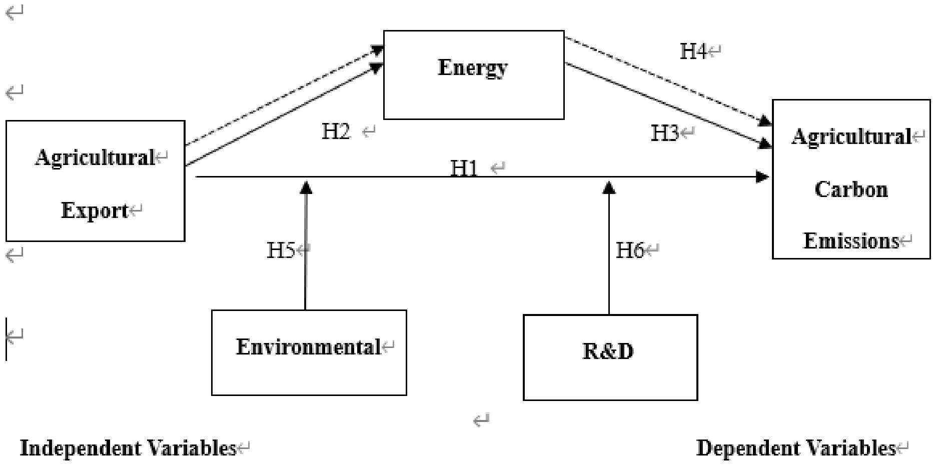

Figure 5.1 Simplified conceptual framework of this study

CONCLUSION

This literature review explores how agricultural exports contribute to Agricultural Carbon Emissions (ACE) within the broader trade–environment nexus, using China as a case study. Grounded in key theories such as the Pollution Haven Hypothesis (PHH), Energy–Environment Mechanism (EEM), Environmental Governance Theory (EGT), Green Innovation Theory (GIT), and the Environmental Kuznets Curve (EKC), this study systematically reviews how trade interacts with energy consumption, institutional regulation, and innovation capacity to influence environmental outcomes. It builds a theoretical framework that integrates mediating and moderating mechanisms, filling several notable gaps in the literature.

First, regarding the research scope, this paper broadens the trade-environment literature into the underexplored agricultural sector. A substantial body of existing work focuses on industrial emissions, overlooking the agricultural domain, particularly in major exporting and emerging economies like China (Doğan et al., 2019; Kamyab et al., 2024; Liu et al., 2020; Saghaian et al., 2022).

Second, in terms of research content, this study incorporates energy consumption as a mediating variable and environmental governance and Research and Development (R&D) investment as moderating variables. Existing studies rarely integrates these mechanisms into a unified framework, focusing instead on direct trade-emission relationship. The inclusion of provincial-level data also enables regional heterogeneity analysis and policy relevance (Edoja et al., 2024; Guo et al., 2022; Jin et al., 2024; Khan et al., 2021; Yılmaz, 2023).

Third, methodologically, while models such as Logarithmic Mean Divisia Index (LMDI), Autoregressive Distributed Lag Model (ARDL), and Stochastic Impacts by Regression on Population, Affluence and Technology (STIRPAT) models are commonly employed, they each present limitations in capturing non-linear and regional dynamics. This study introduces the EKC framework to better model the inverted U-shaped relationship between economic growth and emissions, an approach still rare in agriculture-focused studies. (Yang et al., 2022; Tanveer et al., 2024; Mahmood et al., 2021; Wang & Lv, 2022).

In addition, with respect to data sources, many existing studies reply on uniform national emission coefficients, which fail to capture regional variation. Recent literature highlights the advantages of using data from the China Emission Accounts and Datasets (CEADs), which apply region-specific and IPCC-compliant emission factors to improve the accuracy and comparability of ACE estimates (Guo et al., 2022; Song et al., 2023; Wang et al., 2021).

By addressing these gaps scope, variables, methods, and data, this study enhances the theoretical and empirical understanding of how agricultural trades affects ACE. The integration of energy use and institutional variables into a coherent framework represents a conceptual advance with both research and policy implications. environmental governance, and technological innovation to shape carbon emission outcomes in China.

Future studies should empirically test this framework using regionally disaggregated data, explore cross-country comparisons, and investigate additional mediating mechanisms. Policymakers may also draw on these insights to design low-carbon strategies tailored to the specific conditions of agricultural sectors in export-oriented economies like China.

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