

A crosscultural investigation of sustainable agriculture and sustainable food systems - The economic, social and environmental considerations

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ABSTRACT

Sustainable agriculture has garnered greater attention as a key factor for ensuring future global food security and mitigating environmental degradation and climate change/sustainable development. With the continued growth of the world population, agricultural systems are facing mounting challenges to meet the increasing demand for food while reducing environmental negative impacts. This paper analyzes the importance of agricultural sustainability for sustainable development and it therefore analyzes the extent to which it is pivotal to the accomplishment of major sustainable development goals (2 Zero Hunger, 12 Responsible consumption and production, 13 Climate Action, 15 Life on land). Particular attention is given to China and the United States, India and the EU as the world's largest agricultural producers, to examine how different agricultural systems contribute to sustainable development under contrasting economic, environmental, and policy contexts.

Importance of study: This study is unique in the fact that it studies agriculture as a system of providing food but also generating economic, social and environmental sustainability. Policies, researchers, businesses, and farm communities focused on the pursuit of productivity levels that are environmentally responsible and socially beneficial need to understand how sustainable agricultural practices can facilitate long-term development.

This article employs a qualitative literature review to examine academic journal articles, United Nations reports, and policy documents as well as case studies from various geographic areas. The relevant literature was systematically reviewed with a critical lens to determine common themes, key findings, challenges, and opportunities related to sustainable agriculture. The analysis primarily draws on evidence from China and the United States, while incorporating selected international literature to provide broader context and comparison.

Results showed that sustainable farming has a great impact on increasing food accessibility, decreasing environmental damage, improving resource utilization, and contributing to climate

change abating. Successful factors are related to innovation technology, agricultural extension service, sustainable land management, circular economy practice, and good governance. Yet obstacles such as climate change, financial limitations, policy incoherence, and disparate access to resources are impeding advancement.

The study introduces a comprehensive framework that integrates environmental sustainability, economic sustainability, social sustainability and institutional sustainability as the 4 pillars of sustainable agriculture. It finds that sustainable agriculture is crucial for realizing many of the SDGs and for attaining the long-term sustainability of the globe. Future investigations should be drawn toward empirical, cross-national analyses and assessments of alternative and emerging agricultural technologies that hold promise for agricultural sustainability development. The comparison shows that China has made notable progress through strong government-led policies and technological adoption, whereas the United States demonstrates the importance of innovation, precision agriculture, and market-driven approaches, although both countries continue to face environmental and institutional challenges.

Keywords: Agricultural sustainability, sustainable development goals, cross-national analysis, agricultural technology, food accessibility, global food security, United Nations.

Introduction

The value of agriculture in human development cannot be overstated as it has supported human existence through the provision of food, labour, and income for millennia (World Bank, 2026). Yet, contemporary agri-food systems are challenged by an unprecedented pace of population growth and climate change, alongside environmental and resource degradation and food insecurity. Global food systems will be under even greater pressure in coming decades to increase productivity while conserving natural resources as a result of the expected increasing demands of a growing population (United Nations, 2024), according to the United Nations. Thus, north sustainable agriculture has gained increasing attention from the scientific community, policy makers and international bodies. Sustainable agriculture promotes the notion to simultaneously maintain productive agriculture, sound environment, functional society and economic viability and the satisfaction of today's needs without compromising the needs of the next generation (Food and Agriculture Organization, 2018).

The significance of sustainable agriculture is rooted not only its role in food production but also in the broader context of the sustainable development agenda. Agriculture matters for sustainability in a number of ways, including reducing poverty, enhancing food security, contributing to action on climate, supporting biodiversity and sustainable resource use. And it is crucial to achieving a number of the United Nations Sustainable Development Goals (SDGs), in

particular SDG 2 (Zero Hunger), SDG 12 (Responsible Consumption and Production), SDG 13 (Climate Action), and SDG 15 (Life on Land)(United Nations, 2015). However, many agricultural systems still struggle with issues such as greenhouse gas emissions, land degradation, resource mismanagement, and uneven access to technology and financial resources, despite growing awareness worldwide(Intergovernmental Panel on Climate Change, 2019). Hence it is important to explore how sustainable agricultural approaches can contribute to overcoming these challenges in order to promote sustainable development in the long term.

The importance of this research lies in the fact that it is a comprehensive analysis of sustainable agriculture and its impact situationally at the local and regional as well as at the national and global scales in terms of sustainable development. Although sustainable agriculture has been studied from many different angles, what is needed now is an integration of the various strands, including environmental sustainability, food security, technological innovation, agricultural policy, and global development. In this way, by synthesising evidence from a variety of different disciplinary and policy sources, this review can present a holistic view of the potential for sustainable agriculture to contribute to sustainable development goals (Food and Agriculture Organization, 2018). By investing the experiences of China, the US, India and the EU this study also highlights how different policy frameworks, technological capacities, and institutional arrangements influence the implementation of sustainable agriculture and its contribution to sustainable development. The results could also be valuable for policy-makers, educators, businesses, researchers and farmers interested in promoting more sustainable and resilient agricultural systems.

To achieve these objectives, this study adopts a qualitative literature review methodology. Academic journal articles, United Nations reports, policy documents, and case studies were selected and critically analysed to identify recurring themes, major findings, challenges, and future opportunities. The literature was organised into three key areas: the relationship between agriculture and sustainable development, the contribution of sustainable agriculture to significant Sustainable Development Goals, and global perspectives on sustainable agricultural practices and policies. Through comparative analysis and synthesis of existing research, this study aims to develop a broader understanding of the role agriculture plays in supporting sustainable development.

This paper adds to the debates by offering a vision of sustainable agriculture as one that included environmental, economic, social and institutional dimensions. The next section reviews the literature on agriculture and sustainable development, analyzes the implications of sustainable agriculture for key Sustainable Development Goals, and considers global views on the sustainable practices of agriculture and the challenges involved. A discussion on the emerging key themes from the literature follows, along with a conceptual framework synthesising the

findings is presented, gaps in current research are highlighted and areas for future research are suggested. By means of this analysis, the investigation aims to affirm the importance of sustainable agriculture as a condition for sustainable development.

1. Agriculture and Sustainable Development: An overview

A study from Sarfraz, Iqbal, Wang, Bhutta and Jaffri (2022) analyzed the role of the agricultural resource sector in environmental emissions, especially carbon dioxide and methane, and explored its clear relationship with sustainable development in China. The authors aim to understand how various economic parameters affect these emissions and assess the impact of the sector on environmental sustainability and bioeconomy, thereby addressing the broader issue of balancing agricultural productivity and environmental protection within China's development framework. The paper clearly states that its purpose is to analyze the role of the agricultural resource sector in environmental emissions (CO₂ and methane) and its relationship to sustainable development in China. Its objectives—to understand the economic determinants of emissions and predict future trends—are very clear.

The present study is a quantitative research that utilizes panel data of the World Bank from 2000 to 2021 and support vector regression (SVR). Such a technique can be used to study correlations, nonlinear dependencies and to predict the evolution of the emissions. This study employs statistical tools such as charts to examine the relationship between macroeconomic indicators and greenhouse gas emissions. Further, the authors utilize a machine learning method, support vector regression (SVR), to fit and forecast the nonlinear relationship of carbon dioxide and methane emissions in the agricultural sector as well as the future trend of China's environmental effect. However, I would have preferred to see more robustness checks, i.e. comparisons to other ml models. In addition, the research is based on annual time series data from World Bank rather than use traditional sampling (no survey or experimental sampling). That is suitable for this study, but the outcome relies entirely on the accuracy and completeness of this secondary data.

The main results are the two following: (i) There is a very high positive correlation between carbon dioxide emissions and R&D expenditure (0.98), which suggests that stronger R&D activities could be associated with higher emissions. On the contrary, a very strong negative correlation (−0.97) exists between methane emission and agricultural land, which shows that agricultural land expansion is also related to a reduction in methane emission. The nonlinear relationship between economic factors and emissions is further confirmed by support vector regression (SVR) models, which also foresee that emissions will tend to converge within the next decade as a result of sustainable development policies, emphasizing both the environmental consequences of the industry and the possibilities for managing emissions in the future. These findings significantly contribute to our knowledge of how agricultural activities impact the

environment in China. However, the results are not without limitations: for one, correlation does not equal causation, and whether or not increasing expenditures on R&D actually causes greater carbon dioxide output is not rigorously tested. Second, the SVR estimates are based on the training data from 2000 to 2021 and might be inaccurate in case of significant policy shifts, technological breakthroughs, or climate shocks in the future. Finally, the analysis is conducted only for a limited number of economic variables and the impact of other relevant factors (energy structure, the quality of technological innovation and the degree of policy execution) could not be evaluated, which leads to incomplete conclusions. Hence, the findings are in some sense conclusive to reveal trends and relationships, but they are not strong enough to give a solid causal implication or finding about future trends.

The authors finally obtain that the sector of agricultural resources significantly influences the emissions of carbon dioxide and methane in China, and economic activities are significant in maintaining environmental sustainability. They believe that machine learning models such as support vector regression (SVR) have great potential in analysing and predicting emissions and can assist in designing sustainable agriculture policies. Their findings reinforce the importance of policies that promote an appropriate balance between economic and environmental interests and highlight that emissions are, for the time being, likely to stabilise, but that further endeavours should be devoted towards achieving sustainable development and reducing emissions from China's agri-food system. Nonetheless, it is not clear to what extent the authors offer a comprehensive comparison with related work. A more coherent approach is needed whereby the results are related to the existing literature on emissions, R&D, and sustainable agriculture. Finally, sound scholarship recognizes that correlation is not causation, secondary data (i.e., the World Bank) may miss local or micro-level nuances, and SVR forecasts are highly dependent on training data and may not be able to capture anomalies (such as policy changes and climate shocks).

Later on, Mikhailova, Schlautma, Zurqani, Lin, Hai, Post and Shepherd (2023) examined how land and soil resources can be effectively monitored to support Sustainable Development Goals (SDGs), particularly SDGs 2, 12, 13 and 15. It highlights the limitation of current SDG indicators, which lack specificity and fail to fully capture soil functions such as carbon storage and ecosystem services. The study uses a quantitative geospatial approach, combining remote sensing data (2011–2016) with national soil databases such as SSURGO and STATSGO. GIS techniques are applied to analyse land-use change and calculate soil carbon loss, which is further converted into the social cost of carbon (SC-CO₂). This method is appropriate for large-scale, objective analysis, although it relies on assumptions and secondary data.

The findings show that land development in the United States led to significant environmental impact, including the loss of 4.0×10^{11} kg of soil carbon and an estimated cost of US\$76 billion.

Development affected all soil types and reduced biodiversity, with major impacts concentrated in states such as Texas and Florida. Forests, wetlands, and pastures were particularly affected. However, the study has some limitations. The analysis depends on estimates of carbon loss and cost, introducing uncertainty. In addition, the time range is limited (2011–2016), and national-level data may overlook local variations. While the results clearly show trends, they do not establish direct causation between development policies and environmental degradation. Overall, the study concludes that geospatial monitoring is an effective tool for assessing sustainability and improving SDG indicators. It argues that current frameworks should be expanded to better reflect soil and land dynamics. This suggests that while the study provides strong quantitative evidence, its conclusions should be interpreted cautiously due to data and modelling limitations.

A report by the General Secretary (2018) assessed the global progress and challenges in agriculture, food security, and nutrition, with a focus on achieving Sustainable Development Goal 2 (Zero Hunger). It examines the causes of rising hunger and explores how sustainable and inclusive food systems can be developed. The report uses a synthesis approach, combining data from multiple UN agencies (e.g., FAO, WFP, WHO) and global indicators such as undernourishment and food insecurity rates. This method is appropriate for providing a global overview and identifying broad trends, although it is mainly descriptive and lacks detailed causal analysis.

The findings show that global hunger has increased to 815 million people, driven by factors such as conflict, climate change, economic slowdown, and inequality. The report also highlights multiple forms of malnutrition and structural challenges faced by smallholder farmers. In addition, environmental issues such as biodiversity loss, land degradation, and water stress further threaten food systems. However, the report has some limitations. Its global scope reduces depth and does not provide specific solutions for individual countries. The analysis is largely descriptive, and causation is not fully established. In addition, data gaps and differences between countries may affect reliability. Overall, the report concludes that ending hunger requires integrated, multi-sectoral strategies, including supporting smallholders, improving resource management, and addressing root causes such as poverty and inequality. This suggests that while the report is strong in providing a comprehensive overview, it is more policy-oriented than analytically rigorous.

Furthermore, the 2021 report assesses the role of agricultural technology in transforming agri-food systems to achieve the Sustainable Development Goals, particularly by promoting sustainability, inclusiveness, and resilience. It focuses on how science and technology can be used effectively while ensuring that vulnerable groups are not excluded. The report adopts a qualitative, policy-oriented approach, synthesising global datasets, UN agency reports, and scientific research. It uses a systems-thinking framework, integrating factors such as climate

change, poverty, nutrition, and inequality. This method is appropriate for analysing complex global issues, although it is largely descriptive and does not involve primary data or quantitative testing.

The findings show that global food insecurity remains severe, with up to 811 million people undernourished and 3 billion unable to afford a healthy diet. Food systems also contribute significantly to environmental problems, including 34% of global emissions and biodiversity loss. While technologies such as biotechnology, digital tools, and renewable energy can improve productivity and sustainability, unequal access and weak governance may increase inequality and exclusion. However, the report has limitations. Its analysis is broad and mainly descriptive, lacking detailed empirical testing and causal evidence. In addition, reliance on secondary data and case studies may reduce precision. Challenges such as the digital divide are identified, but methodological limitations are not fully discussed. Overall, the report concludes that technology alone is insufficient and must be supported by inclusive governance and integrated policy frameworks. This suggests that while the report provides strong strategic insight, it is more policy-focused than analytically rigorous.

Lastly, a study by Raoa, Bathlab, Kumarc and Jhad 2018This article aims to examine how agriculture contributes to achieving the Sustainable Development Goals, with a focus on India. It explores how factors such as technological change, markets, institutions, and policies influence poverty reduction, food security, and sustainable resource use. The study uses a thematic literature review of 178 research papers from AGREE conferences, covering key areas such as inequality, technology adoption, markets, and sustainability. It integrates findings from various quantitative methods, including econometric models and productivity analysis. This approach is suitable for identifying patterns across studies, although it depends on the quality and selection of existing research.

Results indicate that agriculture can substantially contribute to SDGs, but the extent of success differs worldwide. Technological change fuels productivity growth, but diffusion is uneven. Income earned from diversification and mechanization can be enhanced in the meantime organic farming can provide higher income though with lower output. But the overall effect is diluted due to the existence of systemic barriers such as gender disparities, credit limitations, and policy restrictions. Nonetheless, the study has its limitations. As a review article, it does not offer novel empirical proof and the conclusions are dependent on the coherence and trustworthiness of the included studies. Also, the dominance of AGREE conference papers as sources may result in selection bias, thus restricting the potential for generalization. In sum, the broad message of the paper is that agriculture would be a key instrument for delivering the SDGs, but this requires regional tailoring of innovations, inclusive policies, and enhanced market access. It seems to

imply that the Paper provides a thorough synthesis of the extant literature albeit drawing conclusions from Secondary Sources.

In summary, agriculture is generally found to be integral to sustainable development and is a determinant of food security, environmental sustainability, economic growth, and social well-being. The available literature reviewed provides an insight into the potential and problems of agricultural development. Although advances in technology, sustainable management of land resources, and befitting policies environment are expected to improve productivity to support the realization of SDG, advancing is hampered by such issues as environmental degradation, disparity, insufficient access to technology, and lack of data. In addition, many studies depend on secondary data, modelling or literature reviews, which constrain the ability to identify direct causal links. Although there are constraints, the literature does suggest that sustainable agriculture development means adopting an integrated approach encompassing economic, environmental and social goals. These results form the basis for the subsequent section focusing on specific strategies, policies or case studies for promoting sustainable agriculture and the extent to which they may effectively contribute to long-term sustainable development.

2. Sustainable agriculture and relevance to significant SDGs

Agriculture plays a central role in sustainable development because it connects food production with economic growth, social well-being, and environmental protection. However, agricultural activities can also contribute to climate change, land degradation, biodiversity loss, and also excessive resource use when they are poorly managed. Sustainable agriculture therefore provides an important approach to balancing higher productivity with the protection of natural resources and rural livelihoods. Its contribution can be understood more clearly by examining its relationship with major Sustainable Development Goals, particularly those concerning hunger, responsible production, climate action, and the conservation of terrestrial ecosystems.

The 2017 UN report is designed to track worldwide development toward the United Nations Sustainable Development Target 2.1 - an end to hunger, food insecurity and malnutrition, including through Sustainable Development Goal 2 (SDG 2, 'end hunger, achieve food security and improved nutrition, and promote sustainable agriculture'). The analysis examines how to meet the 'zerohunger' target through agricultural transformation and rural development, while considering the strong linkages of SDG 2 with other targets such as poverty and climate. The report is intended to provide an update on progress to date, to identify major challenges and lessons learned, and to outline policy directions on governance, coordination and investments. These goals are very much in line with those of the global sustainable development agenda and those discussed at the UN High Level Political Forum. This report follows a multi-agency and policy perspective, rather than a classical academic research methodology. It brings together

country survey data collected during 2017 by UN entities, such as the Food and Agriculture Organization of the United Nations (FAO) and the International Fund for Agricultural Development (IFAD), with global datasets and policy instruments. The analysis is based on a quantitative indicators (hunger and nutrition statistics) and qualitative policy analysis to evaluate the manner in which countries are localizing the SDGs, strengthening national coordination mechanisms and aligning policy. The report is rooted on the UN Decade of Action on Nutrition (2016-2025). It does highlight challenges in cross-target governance (policy fragmentation, limited data capacity) but most certainly does not define these or similar terms from a detailed or technical perspective given the nature of the report as a policy assessment.

The main messages are that although some progress has been made, the challenges; are still enormous. About 70% of the extremely poor in the world depend on farming, but they own little land or access to finance or technology. Urbanization has strained urban and rural food systems, and climate shocks have driven some 108 million people into food insecurity (as at 2016). While 85% of countries have established SDG coordinating bodies, there is a risk of policy fragmentation without sufficient inter-sectoral integration. The Decade of Nutrition has promoted multi-stakeholder engagement, however poor data collection and monitoring capacity still poses a major constraint. These are not final results but they do decidedly point to the trends, risks, and gaps that are undermining the achievement of the Zero Hunger Goal. In light of these findings, the report identifies a threefold transformation path: transforming to an economically viable and socially capable food system; promoting the living standards and adaptive capacities of small-scale food producers, including farmers, fishers, and pastoralists; and scaling up investments in agricultural infrastructure. The report calls for cross-sectoral national policy integration, preferably through national platforms, to limit fragmented ministerial action. The findings of the report are of direct interest to the wider literature and policy discussions on food security, nutrition, climate change and sustainable development and are based on evidence from sources including the State of Food Security and Nutrition in the World (SOFI) and public health research. In general terms, the report cages the realization of

Sustainable Development Goal 2 tightly to the global dialogue and highlights that only through “joined-up” thinking and action can progress be achieved.

The UN reports from 2019 and 2020 explore the development of agricultural extension systems and their role in achieving the 2030 Sustainable Development Goal of "Zero Hunger." The authors focus on how to improve agricultural productivity and ensure food security while simultaneously considering environmental sustainability and socioeconomic development. They particularly emphasize the negative environmental impacts of certain modern agricultural technologies, while also considering the broader social and economic impacts of agricultural activities. The main objective of this paper is to explore how agricultural extension systems can

evolve to support sustainable agriculture, improve food security, and address environmental and institutional challenges. These goals are consistent with the global sustainable development agenda and clearly reflect the research objectives of this paper. This study employs qualitative and conceptual research methods, primarily based on an extensive review of existing literature on agricultural extension, sustainable agriculture, and food security.

Using historical analysis, theoretical discussion, and case studies, the authors review the past trajectory of extension systems and consider potential future trends. This study is not based on original empirical data and experiments but is a synthesis of the insights from prior studies, policy documents, and expert opinions. This is an appropriate method for philosophical review papers to foster the development of concepts and theoretic frameworks, but it is not as rigorous a methodology as that used for a systematic literature review and/or empirical validation. It is analyzed through comparative as thematic discussions. The authors contrast the old production-focused extension systems with new participatory and knowledge-based approaches, focusing on farmer education, technology transfer, and community involvement. Results from this review suggest that although agricultural extension agencies must evolve if they are to better contribute to sustainable agriculture, they will continue to play a central role in aiding improvements in agricultural productivity and food security. The authors identify participatory extension approaches as among the best methods of inducing farmers to adopt sustainable agricultural practices. However, in the absence of quantifiable data and causal assessment, the outputs of this study are largely directed at ideational and strategic levels rather than empirical findings.

The authors conclude that agricultural extension systems are essential for achieving the goal of "zero hunger" because they support productivity growth, food security, and knowledge dissemination. At the same time, they argue that extension systems must continuously evolve, incorporating sustainable development principles, interdisciplinary knowledge, and institutional support. A more holistic approach, combining scientific research, farmer training, and community involvement, is needed to address environmental and socioeconomic challenges. While the paper does not explicitly discuss its limitations, implied shortcomings include a lack of a systematic literature review process and a lack of empirical evidence. Overall, its findings are highly consistent with existing literature on sustainable agriculture and extension systems, reinforcing the widely accepted view on participatory, knowledge-intensive, and sustainability-oriented agricultural development.

A 2023 UN report reviewed research on the circular economy (CE) and agriculture in relation to the Sustainable Development Goals, SDG 2 in particular. It addresses various aspects of resource efficiency, waste reduction, and sustainability application in CE and presents main research trends and gaps. The study is built on a bibliometric analysis of scientific publications employing keyword-based mapping and trend analyses from 2005 to 2020. It is focused on thematic clusters

as well as on the geographical distribution of the body of knowledge. This approach can be used to detect research trends, but it cannot assess quality of research or its impact in the real world. Results indicate an exponential growth of research after 2015 following three major axes: sustainable management of agriculture, bioenergy from waste, and life cycle assessment. Research is focused in Europe and Asia followed, closely, by the Americas, with other locales trailing. The research also suggests that food waste and farm emissions are still significant challenges, and that organic farming is more connected to circular economy principles.

However, the study has limitations. It is based on the selection of databases and keywords which could lead to bias and the omission of some studies. Besides, bibliometric analysis does not evaluate the effectiveness of circular economy measures in practice. The study concludes that, although the circular economy offers a good lens through which to look at sustainable agriculture, more work is needed and adoption needs to be wider. This means that the study is good to map research trends, but it is not able to examine practical impact.

Taken as a whole, these analyses suggest that sustainable agriculture is integral to meeting multiple Sustainable Development Goals, especially SDG 2 (Zero Hunger), while reducing poverty and contributing to climate action and sustainable resource use. The studies uniformly emphasize the need for integrated food systems, agricultural extension, farming education and innovations like the circular economy to enhance food security and environmental sustainability. Yet common challenges such as climate change, resource scarcities, policy incoherence, data deficiency, and unequal knowledge and technology access remain. Although a number of the reviewed reports and publications are focused on policy and are heavily based on secondary data or conceptual discussions, these work provide an important lens on the core approaches required to enable sustainable agriculture development. Taken together, these results provide a solid basis for understanding the role of agriculture in the SDGs and lead to the following section, which will review specific agricultural practices, technologies, or case studies that illustrate demonstrate how SD objectives can be operationalised in agriculture.

3. Sustainable Agriculture from a global perspective

While the Sustainable Development Goals provide a global framework for understanding the importance of sustainable agriculture, their successful implementation depends on how agricultural practices are adopted across different regions of the world. Countries face diverse environmental conditions, economic capacities, and social challenges, meaning that no single approach to sustainable agriculture is universally applicable. Factors such as climate, technology, government policies, and access to financial resources all influence the effectiveness of sustainable farming practices. Therefore, examining sustainable agriculture from a global

perspective is essential for understanding how different nations address common sustainability challenges while adapting solutions to their local contexts.

A study by Sroufe and Watts (2022) explored the pathways for decarbonization of U.S. agriculture, focusing on barriers and opportunities presented by climate change. The authors aimed to understand how the agricultural sector plans to decarbonize over the next 10 to 25 years, especially in the context of changing policy, technology, and market conditions. The research question revolves around identifying and addressing key challenges (e.g., economic feasibility, policy fragmentation, and behavioral inertia) and opportunities (e.g., technological innovation and sustainability incentives) in the agricultural sector's transition to carbon neutrality. The paper's objectives include identifying barriers and opportunities, proposing a scenario-based planning approach, and providing references for policymakers. These objectives are highly consistent with the article's title and abstract, making the purpose and motivation clear. It not only proposes a path forward but also emphasizes the integration of short-term and long-term perspectives, highlighting the practical value and policy relevance of the research.

The study's methodology included a comprehensive review of existing literature, it focusing on decarbonization metrics and targets, such as greenhouse gas (GHG) emissions per unit of agricultural output, soil carbon sequestration levels, energy efficiency of production systems, and adoption of low-emission practices such as cover crops and precision agriculture. The study then analyzed important barriers, such as poor infrastructure of climate-suit technologies, varying regulations among different states, and farmers' reluctance to abandon old practices. Among the identified opportunities are: increasing use of digital monitoring tools, rising consumer interest in sustainable food, and new investments from the federal government in green agriculture. Furthermore, the study employs scenario analysis to assess alternative decarbonization paths by focusing on (a) drivers of change (e.g., governmental regulation, market incentives, climate change) and (b) major uncertainties in technology diffusion and global commodity prices. The authors demonstrate how policy makers can tackle these concerns by flexible regulation, focused subsidies, and multi-stakeholder partnerships. The methodology underpinning the analysis is scenario planning, which considers the uncertainties associated with emissions reduction in agriculture. The authors identified and assessed possible pathway options by literature reviews, followed by the development of future scenarios through the identification and prioritisation of drivers. This method is applicable for addressing problems associated with high levels of complexity and uncertainty, particularly at the nexus of climate and agriculture. Hence, the methodology matches the purpose of the study. Unlike standard statistical sampling, the paper draws on data from literature, industry reports, policy documents and corporate case studies. This line of 'materiality issue' determination is more suitable in strategic analysis for empirical investigation. Hence, although not a quantitative form of sampling, this decision is well aligned

with the aims of the study which are to identify pathways and opportunities, and not to draw statistical inferences about particular groups.

The study's key findings include several drivers of change and uncertainties that affect the decarbonization potential of the agricultural sector. Major sources of emissions include on-farm energy use, soil and fertilizer management, enteric fermentation (a significant source of global methane emissions), manure handling, and post-harvest waste. The study found several promising decarbonization opportunities: improved emission measurement methods (such as satellite imaging and AI-based modeling), emerging national-level climate commitments (such as the USDA's Climate Smart Commodities Initiative), and alignment with multiple UN Sustainable Development Goals—particularly SDG 2 (Zero Hunger), SDG 12 (Responsible Consumption and Production), SDG 13 (Climate Action), and SDG 15 (Life on Land). The findings also highlight the importance of integrating sustainability into corporate agendas, as agricultural companies increasingly focus on material ESG issues and long-term resilience. The analysis integrates existing literature, emissions data, and company case studies to identify key barriers and opportunities for agricultural decarbonization. Scenario planning was then used to prioritize drivers based on their impact and uncertainty, thereby constructing plausible future pathways. This analysis is logically clear and incorporates policy and practical examples, supporting a multidimensional understanding of complex issues. Therefore, it is appropriate. The results are not definitive, but rather offer four possible future scenarios as a reference for decision-making and planning. Because the study employed scenario planning, the results are exploratory and hypothetical, rather than strictly causal. While not definitive, they successfully demonstrate multiple possible pathways and provide directional conclusions for subsequent research and policy.

The authors conclude that while U.S. agriculture faces significant challenges in transitioning to carbon neutrality, it also offers meaningful opportunities for transformation. They propose four different future scenarios: (1) business as usual, which is a continuation of current practices with minimal policy changes; (2) technology-led growth driven by high adoption of precision agriculture and biotech solutions; (3) policy-driven reforms led by carbon pricing, subsidies, and federal mandates; and (4) sustainable transformation, which emphasizes systemic change, regenerative practices, and climate equity. These scenarios show how the industry could develop along different paths, each with different implications for emissions and resilience. The study urges policymakers to act decisively to break with the industrial model of the past century. The study also recommends future research on emissions policy design, finer-scale tracking of CO₂ and methane, infrastructure investment strategies, public-private partnership mechanisms, and incentive programs to support low-carbon transitions at the farm level. The paper's purpose is very clear: to examine how the U.S. agricultural sector can achieve decarbonization over the next

10 to 25 years and to propose pathways and strategies. The authors emphasize agriculture's importance in greenhouse gas emissions and point to its potential in achieving carbon neutrality. The article's conclusion also emphasizes that these scenarios offer decision-makers alternative pathways beyond "business as usual," which is highly consistent with the study's purpose (to identify strategies and action directions). The results are closely linked to the research purpose. The article discusses several limitations, such as the fragmentation of existing research, the neglect of the agricultural sector, and the uncertainties of contextual approaches in practice. Furthermore, the study relies heavily on existing literature and case studies, lacking empirical data validation. These are all acknowledged as limitations. Therefore, it is clear that the authors consciously identify and address research shortcomings. The conclusions not only address the article's research questions but also connect agricultural decarbonization to the global carbon neutrality goal, the Paris Agreement, and the United Nations Sustainable Development Goals (SDGs). The authors emphasize that agriculture is often overlooked in global emissions reduction discussions and call for more policy and practical research. This echoes the prevailing discussion in the existing literature and also highlights the complementary value of the research.

A year earlier, Pietrzyck, Jarze, Bowski and Peterson (2021) study aims to explore the relationship between the food supply chain (FSC), agricultural quality standards, and global trade in the context of sustainable development, particularly under EU policies such as the European Green Deal and the Farm to Fork Strategy. It focuses on how sustainability is integrated into agri-food systems and identifies key challenges in policy coordination and trade practices. The study adopts a qualitative exploratory approach, using an online survey of trade experts from the EU and the United States, alongside analysis of key policy documents such as the Common Agricultural Policy (CAP) and Sustainable Development Goals (SDGs). This method is appropriate for exploring complex relationships, although the use of purposive sampling limits generalisability and may introduce expert bias.

The findings suggest that sustainability is not yet well integrated into global food trade. While quality standards are essential for food safety, they often act as non-tariff barriers due to inconsistent standards and duplicate certification. In addition, weak coordination mechanisms and low awareness among businesses hinder effective implementation. Policies such as the Green Deal and F2F strategy may further increase trade barriers, potentially leading to reduced exports, higher prices, and lower farmer incomes. However, the results are not fully conclusive. The study relies on a small, non-random expert sample, limiting reliability and representativeness. In addition, the qualitative nature of the analysis restricts depth, and findings are based on perceptions rather than empirical measurement. The study also acknowledges gaps in existing research and the complexity of balancing sustainability with trade efficiency. Overall,

the study concludes that although sustainability is a policy priority, there is a significant gap between policy and practice. It recommends improving policy coherence, strengthening stakeholder education, and promoting international standard harmonisation. The findings contribute to the broader debate on sustainable trade but should be interpreted cautiously due to methodological limitations.

In the same year, Weersink et al (2021) examined the short-term impacts and long-term implications of COVID-19 on agri-food systems in the United States and Canada, focusing on supply chain disruptions, labour shortages, and demand changes. It also explores how these effects may lead to structural changes in the sector. The study uses a comparative economic approach, analysing six key commodity groups (cattle, hogs, poultry, dairy, grains/oilseeds, and fruits/vegetables). It relies on year-over-year data on prices, inventories, and trade, supported by expert analysis. This method is appropriate for identifying trends, although it lacks advanced modelling and depends mainly on descriptive data. The findings show that COVID-19 caused major short-term disruptions, particularly due to labour shortages and the shutdown of the hospitality sector. "Just-in-time" supply chains were vulnerable but recovered quickly.

The study also identifies emerging trends such as increased automation, possible industry consolidation, and shifts in consumer behaviour, including more online purchasing and local sourcing. However, the study has several limitations. The analysis is based on short-term data, which reduces reliability when predicting long-term impacts. In addition, the lack of complex models means that causation cannot be clearly established. Future changes such as automation and market restructuring remain uncertain. Overall, the study concludes that the agri-food system is relatively resilient but requires greater flexibility and diversification to improve long-term sustainability. This suggests that while the study is useful for identifying immediate impacts and trends, it is more descriptive than predictive.

Further, a study by Cao and Solangi (2023) identified and prioritized the key obstacles and solutions for sustainable agriculture in China in relation to the Sustainable Development Goals. It focuses on determining which barriers are most critical and which strategies are most effective for supporting sustainable development. The study uses a multi-criteria decision-making approach, combining the analytic hierarchy process (AHP) and simple additive weighting (SAW). Data is derived from literature review and expert evaluation. This method is appropriate for ranking complex factors systematically, although it relies heavily on subjective expert judgement.

The findings show that economic barriers are the most significant, followed by environmental and social factors. Key issues include climate change and lack of financial incentives. The most effective solutions identified are international cooperation, increased investment, and the

promotion of sustainable farming methods such as organic agriculture. However, the study has limitations. The results depend on expert opinions and assigned weights, which may introduce bias. In addition, the model does not test outcomes in real-world conditions, so causation and practical effectiveness remain uncertain. Overall, the study concludes that addressing economic and environmental barriers is essential for achieving SDGs in China. This suggests that while the study provides clear prioritisation through strong methodology, its conclusions are limited by subjectivity and lack of empirical validation.

Overall, the literature demonstrates that sustainable agriculture is a global challenge that extends beyond food production to include climate change mitigation, sustainable trade, economic resilience, and the achievement of multiple Sustainable Development Goals. The reviewed studies highlight the importance of agricultural decarbonisation, sustainable food supply chains, resilient agri-food systems, and effective policy interventions in promoting long-term sustainability. Common themes include the need for technological innovation, international cooperation, stronger policy coordination, and increased investment in sustainable farming practices. At the same time, significant barriers remain, including economic constraints, policy fragmentation, trade tensions, climate-related risks, and uncertainties surrounding future agricultural transformation. Although many studies provide valuable insights, their findings are often limited by reliance on expert judgement, qualitative approaches, scenario planning, or short-term data, meaning that causal relationships cannot always be fully established. Nevertheless, the literature consistently suggests that achieving sustainable agriculture requires integrated strategies that balance environmental, economic, and social objectives. These global perspectives provide an important foundation for the next section, which will examine specific case studies, policies, or practical initiatives to evaluate how sustainable agricultural principles are implemented and how effective they are in achieving sustainable development outcomes.

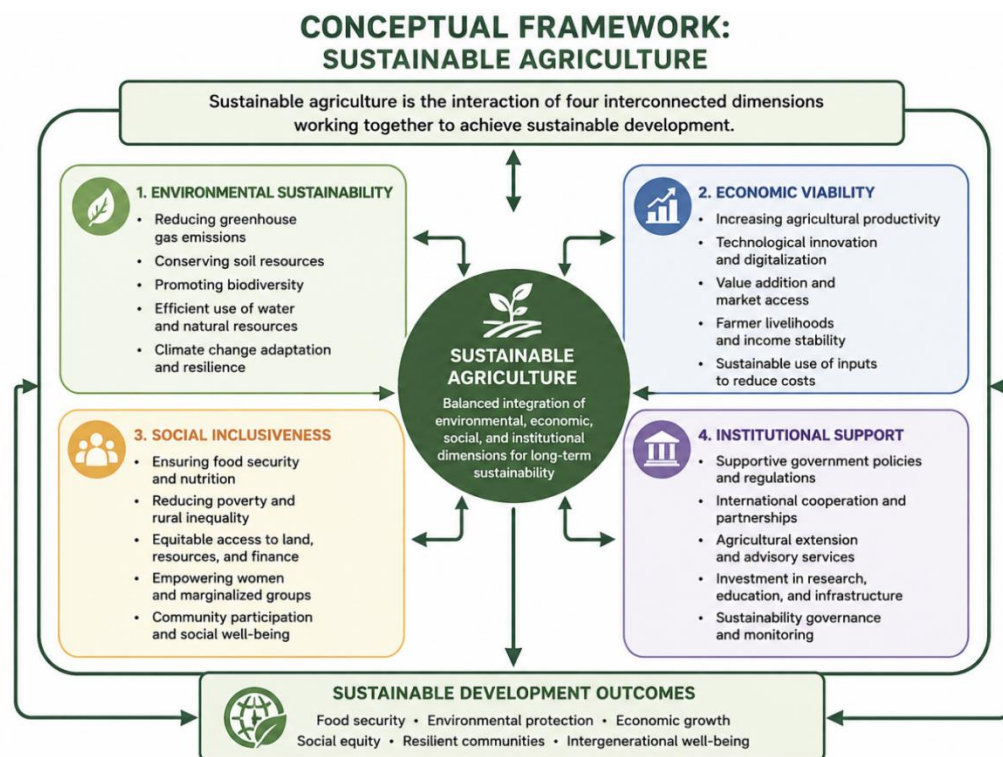
Discussion

Existing studies thoroughly identify sustainable agriculture as a major promoter of sustainable development, and its effects across systems are not limited to food production but rather encompass environmental protection, economic resilience and social well-being. The Food and Agriculture Organization (FAO) notes that sustainable agricultural systems are fundamental to achieving long-term food security and to preserving natural resources for the use of future generations. And the United Nations considers sustainable agriculture also as one of the essential means of implementation in progress towards many other Sustainable Development Goals (SDGs), in particular SDGs 2, 12, 13, and 15 (Food and Agriculture Organization, 2018; United Nations, 2020). Recently, it has been argued that there is yet more need to urge agricultural change. The State of Food and Agriculture 2024 reports the covert environmental, social and health costs of global agrifood systems total some US\$12 trillion per year, or about 10 percent of

global GDP, revealing that we are on an unsustainable path for both food and finance. In the meantime, FAO states that agrifood systems are under escalating strain from climate change, resource degradation, and increased food demand, highlighting the importance of holistic, sustainable agricultural solutions. Taken together, these results constitute compelling evidence that sustainable agriculture ought to be conceptualized as a strategy for accomplishing resilient, inclusive, and environmentally sustainable development rather than a strategy that only produces greater agricultural output.

The literature reviewed demonstrates that sustainable agriculture plays a central role in achieving sustainable development by addressing economic, environmental, and social challenges simultaneously. Across different geographical contexts, sustainable agriculture contributes to food security, poverty reduction, climate change mitigation, resource conservation, and rural development. Although the studies employ different methodologies, ranging from empirical analysis and machine learning models to policy reports and conceptual reviews, they consistently emphasize the importance of balancing agricultural productivity with environmental sustainability. This suggests that agriculture should not be viewed solely as a food production system, but as an integrated component of sustainable development.

Figure 1: A holistic framework to sustainable agriculture (generated by author)



Based on the literature, a holistic conceptual framework can be developed. Sustainable agriculture can be understood as the interaction of four interconnected dimensions: environmental sustainability, economic viability, social inclusiveness, and institutional support. Environmental sustainability includes reducing greenhouse gas emissions, conserving soil resources, and promoting biodiversity. Economic viability focuses on productivity, technological innovation, and farmer livelihoods. Social inclusiveness involves food security, poverty reduction, and equitable access to agricultural resources. Institutional support includes government policies, international cooperation, agricultural extension systems, and sustainability governance. The literature suggests that successful sustainable agricultural systems require progress across all four dimensions rather than focusing on a single objective.

The findings also have important practical implications. From a policy perspective, governments should strengthen support for climate-smart agriculture, sustainable land management, and agricultural innovation while ensuring that policies remain inclusive and coordinated across sectors. From an educational perspective, agricultural extension services and farmer training programs should be expanded to improve knowledge transfer and adoption of sustainable practices. From an industry perspective, businesses should integrate sustainability into supply chains, reduce waste, and invest in low-carbon technologies. These applications are consistent with recent literature on agricultural decarbonisation, circular economy principles, and sustainable food systems, which highlight the need for collaboration among governments, businesses, researchers, and farming communities. For example, the European Union's Common Agricultural Policy (CAP) provides financial incentives for environmentally friendly farming practices, including crop diversification, soil conservation, and biodiversity protection. Similarly, the FAO's Climate-Smart Agriculture (CSA) initiative has supported farmers in countries such as Kenya and Vietnam by promoting climate-resilient farming techniques that improve productivity while reducing environmental impacts.

Overall, the literature supports the argument that sustainable agriculture is essential for achieving several Sustainable Development Goals, particularly SDGs 2, 12, 13, and 15 (United Nations, The 17 Goals; Food and Agriculture Organization, Agrifood Systems and the 2030 Agenda). While technological innovation, sustainable farming practices, and effective governance can significantly improve agricultural sustainability (Rao et al.; Food and Agriculture Organization, Sustainable Food and Agriculture; Weersink et al.), barriers such as climate change, economic constraints, policy fragmentation, and unequal access to resources continue to limit progress (Intergovernmental Panel on Climate Change; United Nations, The Sustainable Development Goals Report 2020; World Bank).

However, this review has several limitations. Most of the literature relies heavily on secondary data, policy reports, expert opinion, or modelling approaches, limiting the ability to establish

causal relationships. In addition, many studies focus on specific countries or regions, which may reduce the generalisability of findings. Future research should include more primary empirical studies, longitudinal analyses, and comparative international research to evaluate the long-term effectiveness of sustainable agricultural practices. Further investigation into emerging technologies, climate adaptation strategies, and the role of developing countries in agricultural sustainability would also contribute to a deeper understanding of how agriculture can support sustainable development in the future.

Conclusion

The unifying message of this study is that sustainable agriculture is not just a way to produce food, but rather an approach to food production that encompasses maintaining environmental sustainability, economic feasibility, social inclusiveness, and institutional support, and that Long-term sustainability development can be realized via this approach. The science unambiguously indicates that sustainable farming systems enhance food security, climate adaptation, biodiversity conservation and rural livelihoods and that they contribute to realizing a suite of Sustainable Development Goals (SDGs). The greatest value of this research lies in its integrative synthesis of the existing literature into a single conceptual model that makes salient the interrelatedness of these domains. The comparative analysis of China and the United States further demonstrates that although the two countries adopt different policy frameworks and agricultural development models, both provide valuable lessons for balancing agricultural productivity with environmental sustainability. Drawing evidence from the environmental, economic, social and policy domains, this review offers a holistic view of sustainable agriculture, such as the critical role of integrated governance and cross-sectoral collaboration, serving as a useful reference for future research, policies and practices to best manage agricultural systems sustainably.

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