Mitig Adapt Strateg Glob Change (2024) 29:44
https://doi.org/10.1007/s11027-024-10139-z

ORIGINAL ARTICLE

Climate-smart agriculture: adoption, impacts, and implications for sustainable development

Wanglin Ma[1] · **Dil Bahadur Rahut**[2]

Received: 8 April 2024 / Accepted: 17 April 2024

Abstract

The 19 papers included in this special issue examined the factors influencing the adoption of climate-smart agriculture (CSA) practices among smallholder farmers and estimated the impacts of CSA adoption on farm production, income, and well-being. Key findings from this special issue include: (1) the variables, including age, gender, education, risk perception and preferences, access to credit, farm size, production conditions, off-farm income, and labour allocation, have a mixed (either positive or negative) influence on the adoption of CSA practices; (2) the variables, including labour endowment, land tenure security, access to extension services, agricultural training, membership in farmers' organizations, support from non-governmental organizations, climate conditions, and access to information consistently have a positive impact on CSA adoption; (3) diverse forms of capital (physical, social, human, financial, natural, and institutional), social responsibility awareness, and digital advisory services can effectively promote CSA adoption; (4) the establishment of climate-smart villages and civil-society organizations enhances CSA adoption by improving their access to credit; (5) CSA adoption contributes to improved farm resilience to climate change and mitigation of greenhouse gas emissions; (6) CSA adoption leads to higher crop yields, increased farm income, and greater economic diversification; (7) integrating CSA technologies into traditional agricultural practices not only boosts economic viability but also contributes to environmental sustainability and health benefits; and (8) there is a critical need for international collaboration in transferring technology for CSA. Overall, the findings of this special issue highlight that through targeted interventions and collaborative efforts, CSA can play a pivotal role in achieving food security, poverty alleviation, and climate resilience in farming communities worldwide and contribute to the achievements of the United Nations Sustainable Development Goals.

Keywords Climate-smart agriculture · Influencing factors · Crop yields · Farm incomes · Research progress · Development programs

Extended author information available on the last page of the article

Published online: 29 April 2024

1 Introduction

Climate change reduces agricultural productivity and leads to greater instability in crop production, disrupting the global food supply and resulting in food and nutritional insecurity. In particular, climate change adversely affects food production through water shortages, pest outbreaks, and soil degradation, leading to significant crop yield losses and posing significant challenges to global food security (Kang et al. 2009; Läderach et al. 2017; Arora 2019; Zizinga et al. 2022; Mirón et al. 2023). United Nations reported that the human population will reach 9.7 billion by 2050. In response, food-calorie production will have to expand by 70% to meet the food demand of the growing population (United Nations 2021). Hence, it is imperative to advocate for robust mitigation strategies that counteract the negative impacts of climate change and enhance the flexibility and speed of response in smallholder farming systems.

A transformation of the agricultural sector towards climate-resilient practices can help tackle food security and climate change challenges successfully. Climate-smart agriculture (CSA) is an approach that guides farmers' actions to transform agrifood systems towards building the agricultural sector's resilience to climate change based on three pillars: increasing farm productivity and incomes, enhancing the resilience of livelihoods and ecosystems, and reducing and removing greenhouse gas emissions from the atmosphere (FAO 2013). Promoting the adoption of CSA practices is crucial to improve smallholder farmers' capacity to adapt to climate change, mitigate its impact, and help achieve the United Nations Sustainable Development Goals.

Realizing the benefits of adopting CSA, governments in different countries and international organizations such as the Consultative Group on International Agricultural Research (CGIAR), the Food and Agriculture Organisation (FAO) of the United Nations, and non-governmental organizations (NGOs) have made great efforts to scale up and out the CSA. For example, climate-smart villages in India (Alam and Sikka 2019; Hariharan et al. 2020) and civil society organizations in Africa, Asia, and Latin America (Waters-Bayer et al. 2015; Brown 2016) have been developed to reduce information costs and barriers and bridge the gap in finance access to promote farmers' adoption of sustainable agricultural practices, including CSA. Besides, agricultural training programs have been used to enhance farmers' knowledge of CSA and their adoption of the technology in Ghana (Zakaria et al. 2020; Martey et al. 2021).

As a result, smallholder farmers worldwide have adopted various CSA practices and technologies (e.g., integrated crop systems, drop diversification, inter-cropping, improved pest, water, and nutrient management, improved grassland management, reduced tillage and use of diverse varieties and breeds, restoring degraded lands, and improved the efficiency of input use) to reach the objectives of CSA (Kpadonou et al. 2017; Zakaria et al. 2020; Khatri-Chhetri et al. 2020; Aryal et al. 2020a; Waaswa et al. 2022; Vatsa et al. 2023). In the Indian context, technologies such as laser land levelling and the happy seeder have been promoted widely for their potential in climate change adaptation and mitigation, offering benefits in terms of farm profitability, emission reduction, and water and land productivity (Aryal et al. 2020b; Keil et al. 2021). In some African countries such as Tanzania and Kenya, climate-smart feeding practices in the livestock sector have been suggested to tackle challenges in feed quality and availability exacerbated by climate change, aiming to improve livestock productivity and resilience (García de Jalón et al. 2017; Shikuku et al. 2017; Radeny et al. 2022).

Several studies have investigated the factors influencing farmers' decisions to adopt CSA practices. They have focused on, for example, farmers' characteristics (e.g., age, gender, and education), farm-level characteristics (e.g., farm size, land fertility, and land tenure security), socioeconomic factors (e.g., economic conditions), institutional factors (e.g., development programs, membership in farmers' organizations, and access to agricultural training), climate conditions, and access to information (Aryal et al. 2018; Tran et al. 2020; Zakaria et al. 2020; Kangogo et al. 2021; Diro et al. 2022; Kifle et al. 2022; Belay et al. 2023; Zhou et al. 2023). For example, Aryal et al. (2018) found that household characteristics (e.g., general caste, education, and migration status), plot characteristics (e.g., tenure of plot, plot size, and soil fertility), distance to market, and major climate risks are major factors determining farmers' adoption of multiple CSA practices in India. Tran et al. (2020) reported that age, gender, number of family workers, climate-related factors, farm characteristics, distance to markets, access to climate information, confidence in the know-how of extension workers, membership in social/agricultural groups, and attitude toward risk are the major factors affecting rice farmers' decisions to adopt CSA technologies in Vietnam. Diro et al.'s (2022) analysis revealed that coffee growers' decisions to adopt CSA practices are determined by their education, extension (access to extension services and participation on field days), and ownership of communication devices, specifically radio in Ethiopia. Zhou et al. 2023) found that cooperative membership significantly increases the adoption of climate-smart agricultural practices among banana-producing farmers in China. These studies provide significant insights regarding the factors influencing farmers' decisions regarding CSA adoption.

A growing body of studies have also estimated the effects of CSA adoption. They have found that CSA practices enhance food security and dietary diversity by increasing crop yields and rural incomes (Amadu et al. 2020; Akter et al. 2022; Santalucia 2023; Tabe-Ojong et al. 2023; Vatsa et al. 2023; Omotoso and Omotayo 2024). For example, Akter et al. (2022) found that adoption of CSA practices was positively associated with rice, wheat, and maize yields and household income, contributing to household food security in Bangladesh. By estimating data from rice farmers in China, Vatsa et al. (2023) reported that intensifying the adoption of climate-smart agricultural practices improved rice yield by 94 kg/mu and contributed to food security. Santalucia (2023) and Omotoso and Omotayo (2024) found that adoption of CSA practices (improved maize varieties and maize-legume intercropping) increases household dietary diversity and food security among smallholders in Tanzania and Nigeria, respectively.

Agriculture is crucial in climate change, accounting for roughly 20% of worldwide greenhouse gas (GHG) emissions. Additionally, it is responsible for approximately 45% of the global emissions of methane, a potent gas that significantly contributes to heat absorption in the atmosphere. CSA adoption improves farm resilience to climate variability (e.g., Makate et al. 2019; Jamil et al. 2021) and mitigates greenhouse gas emissions (Israel et al. 2020; McNunn et al. 2020). For example, Makate et al. (2019) for southern Africa and Jamil et al. (2021) for Pakistan found that promoting CSA innovations is crucial for boosting farmers' resilience to climate change. McNunn et al. (2020) reported that CSA adoption significantly reduces greenhouse gas emissions from agriculture by increasing soil organic carbon stocks and decreasing nitrous oxide emissions.

Although a growing number of studies have enriched our understanding of the determinants and impacts of ICT adoption, it should be emphasized that no one-size-fits-all approach exists for CSA technology adoption due to geographical and environmental variability. The definitions of CSA should also be advanced to better adapt to changing climate and regional production conditions. Clearly, despite the extensive research on CSA, several gaps remain. First, there is a lack of comprehensive studies that consolidate findings across different geographical regions to inform policymaking effectively. The calls for studies on literature review and meta-analysis to synthesize the findings of the existing studies to make our understanding generalized. Second, although the literature on determinants of CSA adoption is becoming rich, there is a lack of understanding of how CSA adoption is influenced by different forms of capital, social responsibility awareness of farmers' cultivating family farms, and digital advisory services. Third, there is a lack of understanding of how climate-smart villages and civil society organizations address farmers' financial constraints and encourage them to adopt modern sustainable agricultural practices, including CSA practices. Fourth, very few studies have explored how CSA adoption influences the benefit–cost ratio of farm production, factor demand, and input substitution. Fifth, no previous studies have reported the progress of research on CSA. Addressing these gaps is crucial for designing and implementing effective policies and programs that support the widespread adoption of CSA practices, thereby contributing to sustainable agricultural development and climate resilience.

We address the research gaps mentioned above and extend the findings in previous studies by organizing a Special Issue on "Climate-Smart Agriculture: Adoption, Impacts, and Implications for Sustainable Development" in the *Mitigation and Adaptation Strategies for Global Change* (MASGC) journal. We aim to collect high-quality theoretical and applied research papers discussing CSA and seek to comprehensively understand the associations between CSA and sustainable rural and agricultural development. To achieve this goal, we aim to find answers to these questions: What are the CSA practices and technologies (either single or multiple) that are currently adopted in smallholder farming systems? What are the key barriers, challenges, and drivers of promoting CSA practices? What are the impacts of adopting these practices? Answers to these questions will help devise appropriate solutions for promoting sustainable agricultural production and rural development. They will also provide insights for policymakers to design appropriate policy instruments to develop agricultural practices and technologies and promote them to sustainably enhance the farm sector's resilience to climate change and increase productivity.

Finally, 19 papers were selected after a rigorous peer-review process and published in this special issue. We collected 10 papers investigating the determinants of CSA adoption. Among them, four papers investigated the determinants of CSA adoption among smallholders by reviewing and summarizing the findings in the literature and conducting a meta-analysis. Three papers explored the role of social-economic factors on ICT adoption, including capital, social responsibility awareness, and digital advisory services. Besides, three papers examined the associations between external development interventions, including climate-smart villages and civil-society initiatives, and CSA adoption. We collected eight papers exploring the impacts of CSA adoption. Among them, one paper conducted a comprehensive literature review to summarize the impacts of CSA adoption on crop yields, farm income, and environmental sustainability. Six papers estimated the impacts of CSA adoption on crop yields and farm income, and one paper focused on the impact of CSA adoption on factor demand and input substitution. The last paper included in this special issue delved into the advancements in technological innovation for agricultural adaptation within the context of climate-smart agriculture.

The structure of this paper is as follows: Section 2 summarizes the papers received in this special issue. Section 3 introduces the international conference that was purposely organized for the special issue. Section 4 summarizes the key findings of the 19 papers published in the special issue, followed by a summary of their policy implications, presented in Section 5. The final section provides a brief conclusion.

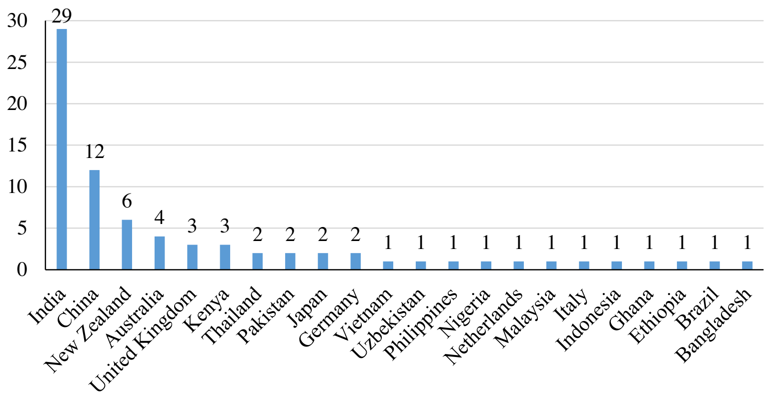

Fig. 1 Distributions of 77 received manuscripts by corresponding authors' countries

2 Summary of received manuscripts

The special issue received 77 submissions, with the contributing authors hailing from 22 countries, as illustrated in Fig. 1. This diversity highlights the global interest and wide-ranging contributions to the issue. Notably, over half of these submissions (53.2%) originated from corresponding authors in India and China, with 29 and 12 manuscripts, respectively. New Zealand authors contributed six manuscripts, while their Australian counterparts submitted four. Following closely, authors from the United Kingdom and Kenya each submitted three manuscripts. Authors from Thailand, Pakistan, Japan, and Germany submitted two manuscripts each. The remaining 12 manuscripts came from authors in Vietnam, Uzbekistan, the Philippines, Nigeria, the Netherlands, Malaysia, Italy, Indonesia, Ghana, Ethiopia, Brazil, and Bangladesh.

Among the 77 received manuscripts, 30 were desk-rejected by the guest editors because they did not meet the aims and scope of the special issue, and the remaining 47, considered candidate papers for the special issue, were sent for external review. The decision on each manuscript was made based on review reports of 2–4 experts in this field. The guest editors also read and commented on each manuscript before they made decisions.

3 ADBI virtual international conference

3.1 Selected presentations

The guest editors from Lincoln University (New Zealand) and the Asian Development Bank Institute (ADBI) (Tokyo, Japan) organized a virtual international conference on the special issue theme "*Climate-Smart Agriculture: Adoption, Impacts, and Implications for Sustainable Development*". The conference was organized on 10–11 October 2023 and was supported by the ADBI.[1] As previously noted, the guest editors curated a selection of 47

[1] The conference agenda, biographies of the speakers, and conference recordings are available at the ADBI website: https://www.adb.org/news/events/climate-smart-agriculture-adoption-impacts-and-implications-for-sustainable-development.

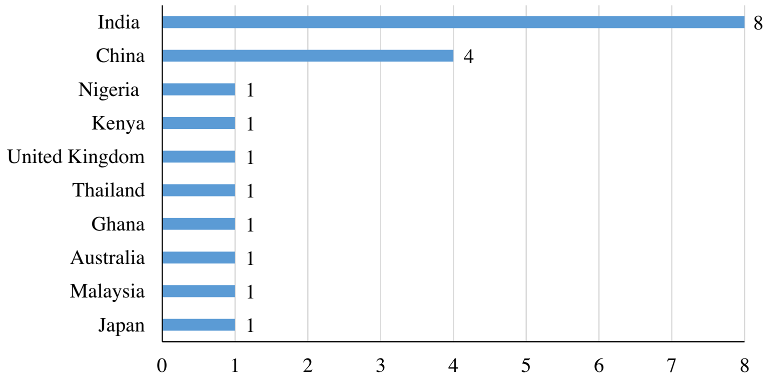

Fig. 2 Distributions of selected presentations by corresponding authors' countries

manuscripts from the pool of 77 submissions, identifying them as potential candidates for inclusion in the special issue, and sent them out for external review. Given the logistical constraints of orchestrating a two-day conference, the guest editors ultimately extended invitations to 20 corresponding authors. These authors were invited to present their work at the virtual international conference.

Figure 2 illustrates the native countries of the presenters, showing that the presenters were from 10 different countries. Most of the presenters were from India, accounting for 40% of the presenters. This is followed by China, where the four presenters were originally from. The conference presentations and discussions proved immensely beneficial, fostering knowledge exchange among presenters, discussants, and participants. It significantly allowed presenters to refine their manuscripts, leveraging the constructive feedback from discussants and fellow attendees.

3.2 Keynote speeches

The guest editors invited two keynote speakers to present at the two-day conference. They were Prof. Edward B. Barbier from the Colorado State University in the United States[2] and Prof. Tatsuyoshi Saijo from Kyoto University of Advanced Science in Japan.[3]

Prof. Edward Barbier gave a speech, "*A Policy Strategy for Climate-Smart Agriculture for Sustainable Rural Development*", on 10th October 2023. He outlined a strategic approach for integrating CSA into sustainable rural development, particularly within emerging markets and developing economies. He emphasized the necessity of CSA and nature-based solutions (NbS) to tackle food security, climate change, and rural poverty simultaneously. Highlighting the substantial investment needs and the significant role of international and domestic financing, Prof. Barbier advocated reducing harmful subsidies in agriculture, forestry, fishing, and fossil fuel consumption to redirect funds toward CSA and NbS investments. He also proposed the implementation of a tropical carbon tax as an innovative financing mechanism. By focusing on recycling environmentally harmful subsidies and leveraging additional funding through public and private investments, Prof.

[2] Profile of Prof. Edward B. Barbie: http://www.edwardbbarbier.com/.

[3] Google Scholar of Prof. Tatsuyoshi Saijo: https://scholar.google.co.nz/citations?user=ju72inUAAAAJ&hl=en&oi=ao.

Barbier's strategy aims to foster a "win–win" scenario for climate action and sustainable development, underscoring the urgency of adopting comprehensive policies to mobilize the necessary resources for these critical investments.

Prof. Tatsuyoshi Saijo, gave his speech, "*Future Design*", on 11th October 2023. He explored the significant impact of the Haber–Bosch process on human civilization and the environment. Prof. Saijo identifies this process, which synthetically fixed nitrogen from the atmosphere to create ammonia for fertilizers and other products, as the greatest invention from the twentieth century to the present, fundamentally transforming the world's food production and enabling the global population and industrial activities to expand dramatically. He also discussed the environmental costs of this technological advancement, including increased greenhouse gas emissions, pollution, and contribution to climate change. Prof. Saijo then introduced the concept of "Future Design" as a method to envision and implement sustainable social systems that consider the well-being of future generations. He presented various experiments and case studies from Japan and beyond, showing how incorporating perspectives of imaginary future generations into decision-making processes can lead to more sustainable choices. By doing so, Prof. Saijo suggested that humanity can address the "Intergenerational Sustainability Dilemma" and potentially avoid the ecological overshoot and collapse faced by past civilizations like Easter Island. He called for a redesign of social systems to activate "futurability", where individuals derive happiness from decisions that benefit future generations, ultimately aiming to ensure the long-term survival of humankind amidst environmental challenges.

4 Summary of published articles

As a result of a rigorous double-anonymized reviewing process, the special issue accepted 19 articles for publication. These studies have investigated the determinants and impacts of CSA adoption. Table 1 in the Appendix summarises the CSA technologies and practices considered in each paper. Below, we summarize the key findings of the contributions based on their research themes.

4.1 Determinants of CSA adoption among smallholders

4.1.1 Influencing factors of CSA adoption from literature review

Investigating the factors influencing farmers' adoption of CSA practices through a literature review helps offer a comprehensive understanding of the multifaceted determinants of CSA adoption. Investigating the factors influencing farmers' adoption of CSA practices through a literature review helps provide a comprehensive understanding of the determinants of CSA adoption. Such analyses help identify consistent trends and divergences in how different variables influence farmers' CSA adoption decisions. In this special issue, we collected four papers that reviewed the literature and synthesized the factors influencing farmers' decisions to adopt CSA.

Li, Ma and Zhu's paper, "*A systematic literature review of factors influencing the adoption of climate-smart agricultural practices*", conducted a systematic review of the literature on the adoption of CSA, summarizing the definitions of CSA practices and the factors that influence farmers' decisions to adopt these practices. The authors reviewed 190 studies published between 2013 and 2023. They broadly defined CSA practices as "agricultural production-related and unrelated practices that can help adapt to climate change and increase agricultural outputs". Narrowly, they defined CSA practices as "agricultural production-related practices that can effectively adapt agriculture to climate change and reinforce agricultural production capacity". The review identified that many factors, including age, gender, education, risk perception, preferences, access to credit, farm size, production conditions, off-farm income, and labour allocation, have a mixed (positive or negative) influence on the adoption of CSA practices. Variables such as labour endowment, land tenure security, access to extension services, agricultural training, membership in farmers' organizations, support from non-governmental organizations (NGOs), climate conditions, and access to information were consistently found to positively influence CSA practice adoption.

Thottadi and Singh's paper, "*Climate-smart agriculture (CSA) adaptation, adaptation determinants and extension services synergies: A systematic review*"", reviewed 45 articles published between 2011 and 2022 to explore different CAS practices adopted by farmers and the factors determining their adoption. They found that CSA practices adopted by farmers can be categorized into five groups. These included resilient technologies (e.g., early maturing varieties, drought-resistant varieties, and winter ploughing), management strategies (e.g., nutrient management, water management, and pest management), conservation technologies (e.g., vermicomposting and residue management, drip and sprinkler irrigation, and soil conservation), diversification of income security (e.g., mixed farming, livestock, and crop diversification), and risk mitigation strategies (e.g., contingent planning, adjusting plant dates, and crop insurance). They also found that farmers' decisions to adopt CSA practices are mainly determined by individual characteristics (age, gender, and education), socioeconomic factors (income and wealth), institutional factors (social group, access to credit, crop insurance, distance, land tenure, and rights), behavioural factors (climate perception, farmers' perception on CSA, Bookkeeping), and factor endowments (family labour, machinery, and land size). The authors emphasized that extension services improved CSA adaptation by reducing information asymmetry.

Naveen, Datta, Behera and Rahut's paper, "*Climate-Smart Agriculture in South Asia: Exploring Practices, Determinants, and Contribution to Sustainable Development Goals*", offered a comprehensive systematic review of 78 research papers on CSA practice adoption in South Asia. Their objective was to assess the current implementation of CSA practices and to identify the factors that influence farmers' decisions to adopt these practices. They identified various CSA practices widely adopted in South Asia, including climate-resilient seeds, zero tillage, water conservation, rescheduling of planting, crop diversification, soil conservation and water harvesting, and agroforestry. They also identified several key factors that collectively drive farmers' adoption of CSA practices. These included socioeconomic factors (age, education, livestock ownership, size of land holdings, and market access), institutional factors (access to information and communication technology, availability of credit, input subsidies, agricultural training and demonstrations, direct cash transfers, and crop insurance), and climatic factors (notably rising temperatures, floods, droughts, reduced rainfall, and delayed rainfall).

Wang, Wang and Fu's paper, "*Can social networks facilitate smallholders' decisions to adopt Climate-smart Agriculture technologies? A three-level meta-analysis*", explored the influence of social networks on the adoption of CSA technologies by smallholder farmers through a detailed three-level meta-analysis. This analysis encompassed 26 empirical studies, incorporating 150 effect sizes. The authors reported a modest overall effect size of 0.065 between social networks and the decision-making process for CSA technology adoption, with an 85.21% variance observed among the sample effect sizes. They found that over half (55.17%) of this variance was attributed to the differences in outcomes within each study, highlighting the impact of diverse social network types explored across the studies as significant contributors. They did not identify publication bias in this field. Among the three types of social networks (official-advising network, peer-advising network, and kinship and friendship network), kinship and friendship networks are the most effective in facilitating smallholders' decisions to adopt climate-smart agriculture technologies.

4.1.2 Socioeconomic factors influencing CSA adoption

We collected three papers highlighting the diverse forms of capital, social responsibility awareness, and effectiveness of digital advisory services in promoting CSA in India, China and Ghana. These studies showcase how digital tools can significantly increase the adoption of CSA technologies, how social responsibility can motivate CSA practices and the importance of various forms of capital in CSA strategy adoption.

Sandilya and Goswami's paper, "*Effect of different forms of capital on the adoption of multiple climate-smart agriculture strategies by smallholder farmers in Assam, India*", delved into the determinants behind the adoption of CSA strategies by smallholder farmers in Nagaon district, India, a region notably prone to climate adversities. The authors focused on six types of capital: physical, social, human, financial, natural, and institutional. They considered four CSA practices: alternate land use systems, integrated nutrient management, site-specific nutrient management, and crop diversification. Their analyses encompassed a dual approach, combining a quantitative analysis via a multivariate probit model with qualitative insights from focus group discussions. They found that agricultural cooperatives and mobile applications, both forms of social capital, play a significant role in facilitating the adoption of CSA. In contrast, the authors also identified certain barriers to CSA adoption, such as the remoteness of farm plots from all-weather roads (a component of physical capital) and a lack of comprehensive climate change advisories (a component of institutional capital). Furthermore, the authors highlighted the beneficial impact of irrigation availability (a component of physical capital) on embracing alternate land use and crop diversification strategies. Additionally, the application of indigenous technical knowledge (a component of human capital) and the provision of government-supplied seeds (a component of institutional capital) were found to influence the adoption of CSA practices distinctly.

Ye, Zhang, Song and Li's paper, "*Social Responsibility Awareness and Adoption of Climate-smart Agricultural Practices: Evidence from Food-based Family Farms in China*", examined whether social responsibility awareness (SRA) can be a driver for the adoption of CSA on family farms in China. Using multiple linear regression and hierarchical regression analyses, the authors analyzed data from 637 family farms in five provinces (Zhejiang, Shandong, Henan, Heilongjiang, and Hebei) in China. They found that SRA positively impacted the adoption of CSA practice. Pro-social motivation and impression management motivation partially and completely mediated the relationship between SRA and the adoption of CSA practices.

Asante, Ma, Prah and Temoso's paper, "*Promoting the adoption of climate-smart agricultural technologies among maize farmers in Ghana: Using digital advisory services*", investigated the impacts of digital advisory services (DAS) use on CSA technology adoption and estimated data collected from 3,197 maize farmers in China. The authors used a recursive bivariate probit model to address the self-selection bias issues when farmers use DAS. They found that DAS notably increases the propensity to adopt drought-tolerant seeds, zero tillage, and row planting by 4.6%, 4.2%, and 12.4%, respectively. The average treatment effect on the treated indicated that maize farmers who use DAS are significantly more likely to adopt row planting, zero tillage, and drought-tolerant seeds—by 38.8%, 24.9%, and 47.2%, respectively. Gender differences in DAS impact were observed; male farmers showed a higher likelihood of adopting zero tillage and drought-tolerant seeds by 2.5% and 3.6%, respectively, whereas female farmers exhibited a greater influence on the adoption of row planting, with a 2.4% probability compared to 1.5% for males. Additionally, factors such as age, education, household size, membership in farmer-based organizations, farm size, perceived drought stress, perceived pest and disease incidence, and geographic location were significant determinants in the adoption of CSA technologies.

4.1.3 Climate-smart villages and CSA adoption

Climate-Smart Villages (CSVs) play a pivotal role in promoting CSA by significantly improving farmers' access to savings and credit, and the adoption of improved agricultural practices among smallholder farmers. CSV interventions demonstrate the power of community-based financial initiatives in enabling investments in CSA technologies. In this special issue, we collected two insightful papers investigating the relationship between CSVs and the adoption of CSA practices, focusing on India and Kenya.

Villalba, Joshi, Daum and Venus's paper, "*Financing Climate-Smart Agriculture: A Case Study from the Indo-Gangetic Plains*", investigated the adoption and financing of CSA technologies in India, focusing on two capital-intensive technologies: laser land levelers and happy seeders. Conducted in Karnal, Haryana, within the framework of Climate-Smart-Villages, the authors combined data from a household survey of 120 farmers, interviews, and focus group discussions with stakeholders like banks and cooperatives. The authors found that adoption rates are high, with 77% for laser land levelers and 52% for happy seeders, but ownership is low, indicating a preference for renting from Custom-Hiring Centers. Farmers tended to avoid formal banking channels for financing, opting instead for informal sources like family, savings, and money lenders, due to the immediate access to credit and avoidance of bureaucratic hurdles. The authors suggested that institutional innovations and governmental support could streamline credit access for renting CSA technologies, emphasizing the importance of knowledge transfer, capacity building, and the development of digital tools to inform farmers about financing options. This research highlights the critical role of financing mechanisms in promoting CSA technology adoption among smallholder farmers in climate-vulnerable regions.

Asseldonk, Oostendorp, Recha, Gathiaka, Mulwa, Radeny Wattel and Wesenbeeck's paper, "*Distributional impact of climate-smart villages on access to savings and credit and adoption of improved climate-smart agricultural practices in the Nyando Basin, Kenya*", investigated the impact of CSV interventions in Kenya on smallholder farmers' access to savings, credit, and adoption of improved livestock breeds as part of CSA practices. The authors employed a linear probability model to estimate a balanced panel of 118 farm households interviewed across 2017, 2019, and 2020. They found that CSV interventions significantly increased the adoption of improved livestock breeds and membership in savings and credit groups, which further facilitated the adoption of these improved breeds. The findings highlighted that community-based savings and loan initiatives effectively enable farmers to invest in CSA practices. Although there was a sustained positive trend in savings and loans group membership, the adoption of improved livestock did not show a similar sustained increase. Moreover, the introduction of improved breeds initially benefited larger livestock owners more. However, credit availability was found to reduce this inequity in ownership among participants, making the distribution of improved livestock more equitable within CSVs compared to non-CSV areas, thus highlighting the potential of CSV interventions to reduce disparities in access to improved CSA practices.

4.1.4 Civil-society initiatives and CSA adoption

Civil society initiatives are critical in promoting CSA by embedding its principles across diverse agricultural development projects. These initiatives enhance mitigation, adaptation, and food security efforts for smallholder farmers, demonstrating the importance of varied implementation strategies to address the challenges of CSA. We collected one paper investigating how civil society-based development projects in Asia and Africa incorporated CSA principles to benefit smallholder farmers and local communities.

Davila, Jacobs, Nadeem, Kelly and Kurimoto's paper, "*Finding climate smart agriculture in civil-society initiatives*", scrutinized the role of international civil society and non-government organizations (NGOs) in embedding CSA principles within agricultural development projects aimed at enhancing mitigation, adaptation, and food security. Through a thematic analysis of documentation from six projects selected on the basis that they represented a range of geographical regions (East Africa, South, and Southeast Asia) and initiated since 2009, the authors assessed how development programs incorporate CSA principles to support smallholder farmers under CSA's major pillars. They found heterogeneous application of CSA principles across the projects, underscoring a diversity in implementation strategies despite vague definitions and focuses of CSA. The projects variedly contributed to greening and forests, knowledge exchange, market development, policy and institutional engagement, nutrition, carbon and climate action, and gender considerations.

4.2 Impacts of CSA adoption

4.2.1 Impacts of CSA adoption from literature review

A comprehensive literature review on the impacts of CSA adoption plays an indispensable role in bridging the gap between theoretical knowledge and practical implementation in the agricultural sector. In this special issue, we collected one paper that comprehensively reviewed the literature on the impacts of CSA adoption from the perspective of the triple win of CSA.

Zheng, Ma and He's paper, "*Climate-smart agricultural practices for enhanced farm productivity, income, resilience, and Greenhouse gas mitigation: A comprehensive review*", reviewed 107 articles published between 2013–2023 to distill a broad understanding of the impacts of CSA practices. The review categorized the literature into three critical areas of CSA benefits: (a) the sustainable increase of agricultural productivity and incomes; (b) the adaptation and enhancement of resilience among individuals and agrifood systems to climate change; and (c) the reduction or avoidance of greenhouse gas (GHG) emissions where feasible. The authors found that CSA practices significantly improved farm productivity and incomes and boosted technical and resource use efficiency. Moreover, CSA practices strengthened individual resilience through improved food consumption, dietary diversity, and food security while enhancing agrifood systems' resilience by mitigating production risks and reducing vulnerability. Additionally, CSA adoption was crucial in lowering Greenhouse gas emissions and fostering carbon sequestration in soils and biomass, contributing to improved soil quality.

4.2.2 Impacts on crop yields and farm income

Understanding the impact of CSA adoption on crop yields and income is crucial for improving agricultural resilience and sustainability. In this special issue, we collected three papers highlighting the transformative potential of CSA practices in boosting crop yields, commercialization, and farm income. One paper focuses on India and the other concentrates on Ghana and Kenya.

Tanti, Jena, Timilsina and Rahut's paper, "*Enhancing crop yields and farm income through climate-smart agricultural practices in Eastern India*", examined the impact of CSA practices (crop rotation and integrated soil management practices) on crop yields and incomes. The authors used propensity score matching and the two-stage least square model to control self-selection bias and endogeneity and analyzed data collected from 494 farm households in India. They found that adopting CSA practices increases agricultural income and paddy yield. The crucial factor determining the adoption of CSA practices was the income-enhancing potential to transform subsistence farming into a profoundly ingrained farming culture.

Asante, Ma, Prah and Temoso's paper, "*Farmers' adoption of multiple climate-smart agricultural technologies in Ghana: Determinants and impacts on maize yields and net farm income*", investigated the factors influencing maize growers' decisions to adopt CSA technologies and estimated the impact of adopting CSA technologies on maize yields and net farm income. They considered three CSA technology types: drought-resistant seeds, row planting, and zero tillage. The authors used the multinomial endogenous switching regression model to estimate the treatment effect of CSA technology adoption and analyze data collected from 3,197 smallholder farmers in Ghana. They found that farmer-based organization membership, education, resource constraints such as lack of land, access to markets, and production shocks such as perceived pest and disease stress and drought are the main factors that drive farmers' decisions to adopt CSA technologies. They also found that integrating any CSA technology or adopting all three CSA technologies greatly enhances maize yields and net farm income. Adopting all three CSA technologies had the largest impact on maize yields, while adopting row planting and zero tillage had the greatest impact on net farm income.

Mburu, Mburu, Nyikal, Mugera and Ndambi's paper, "*Assessment of Socioeconomic Determinants and Impacts of Climate-Smart Feeding Practices in the Kenyan Dairy Sector*", assessed the determinants and impacts of adopting climate-smart feeding practices (fodder and feed concentrates) on yield, milk commercialization, and household income. The authors used multinomial endogenous switching regression to account for self-selection bias arising from observable and unobservable factors and estimated data collected from 665 dairy farmers in Kenya. They found that human and social capital, resource endowment, dairy feeding systems, the source of information about feeding practices, and perceived characteristics were the main factors influencing farmers' adoption of climate-smart feeding practices. They also found that combining climate-smart feed concentrates and fodder significantly increased milk productivity, output, and dairy income. Climate-smart feed concentrates yielded more benefits regarding dairy milk commercialization and household income than climate-smart fodder.

4.2.3 Impacts on crop yields

Estimating the impacts of CSA adoption on crop yields is crucial for enhancing food security, improving farmers' resilience to climate change, and guiding policy and investment towards sustainable agricultural development. In this special issue, we collected one paper that provided insights into this field.

Singh, Bisaria, Sinha, Patasaraiya and Sreerag's paper, "*Developing A Composite Weighted Indicator-based Index for Monitoring and Evaluating Climate-Smart Agriculture in India*", developed a composite index based on a weighted index to calculate the Climate Smart Score (CSS) at the farm level in India and tested the relationship between computed CSS and farm-level productivity. Through an intensive literature review, the authors selected 34 indicators, which were then grouped into five dimensions for calculating CSS. These dimensions encompassed governance (e.g., land ownership, subsidized fertilizer, and subsidized seeds), farm management practices (mulching, zero tillage farming, and inter-cropping and crop diversification), environment management practices (e.g., not converting forested land into agricultural land and Agroforestry/plantation), energy management (e.g., solar water pump and Biogas digester), and awareness and training (e.g., knowledge of climate-related risk and timely access to weather and agro-advisory). They tested the relationship between CSS and farm productivity using data collected from 315 farmers. They found that improved seeds, direct seeding of rice, crop diversification, zero tillage, agroforestry, crop residue management, integrated nutrient management, and training on these practices were the most popular CSA practices the sampled farmers adopted. In addition, there was a positive association between CSS and paddy, wheat, and maize yields. This finding underscores the beneficial impact of CSA practices on enhancing farm productivity.

4.2.4 Impacts on incomes and benefit–cost ratio

Understanding the income effects of CSA adoption is crucial for assessing its impact on household livelihoods, farm profitability, and income diversity. Quantifying income enhancements would contribute to informed decision-making and investment strategies to improve farming communities' economic well-being. In this special issue, we collected two papers looking into the effects of CSA adoption on income.

Sang, Chen, Hu and Rahut's paper, "*Economic benefits of climate-smart agricultural practices: Empirical investigations and policy implications*", investigated the impact of CSA adoption intensity on household income, net farm income, and income diversity. They used the two-stage residual inclusion model to mitigate the endogeneity of CSA adoption intensity and analyzed the 2020 China Rural Revitalization Survey data. They also used the instrumental-variable-based quantile regression model to investigate the heterogeneous impacts of CSA adoption intensity. The authors found that the education level of the household head and geographical location determine farmers' adoption intensity of CSAs.CSA practices. The higher levels of CSA adoption were positively and significantly associated with higher household income, net farm income, and income diversity. They also found that while the impact of CSA adoption intensity on household income escalates across selected quantiles, its effect on net farm income diminishes over these quantiles. Additionally, the study reveals that CSA adoption intensity notably enhances income diversity at the 20th quantile only.

Kandulu, Zuo, Wheeler, Dusingizimana and Chagund's paper, "*Influence of climate-smart technologies on the success of livestock donation programs for smallholder farmers in Rwanda*", investigated the economic, environmental, and health benefits of integrating CSA technologies —specifically barns and biogas plants—into livestock donation programs in Rwanda. Employing a stochastic benefit–cost analysis from the perspective of the beneficiaries, the authors assessed the net advantages for households that receive heifers under an enhanced program compared to those under the existing scheme. They found that incorporating CSA technologies not only boosts the economic viability of these programs but also significantly increases the resilience and sustainability of smallholder farming systems. More precisely, households equipped with cows and CSA technologies can attain net benefits up to 3.5 times greater than those provided by the current program, with the benefit–cost ratios reaching up to 5. Furthermore, biogas technology reduces deforestation, mitigating greenhouse gas emissions, and lowering the risk of respiratory illnesses, underscoring the multifaceted advantages of integrating such innovations into livestock donation initiatives.

4.2.5 Impacts on factor demand and input substitution

Estimating the impacts of CSA adoption on factor demand and input substitution is key to optimizing resource use, reducing environmental footprints, and ensuring agricultural sustainability by enabling informed decisions on efficient input use and technology adoption. In this field, we collected one paper that enriched our understanding in this field. Understanding the impacts of CSA adoption on factor demand, input substitution, and financing options is crucial for promoting sustainable farming in diverse contexts. In this special issue, we collected one paper comprehensively discussing how CSA adoption impacted factor demand and input substitution.

Kehinde, Shittu, Awe and Ajayi's paper, "*Effects of Using Climate-Smart Agricultural Practices on Factor Demand and Input Substitution among Smallholder Rice Farmers in Nigeria*", examined the impacts of agricultural practices with CSA potential (AP-CSAPs) on the demand of labour and other production factors (seed, pesticides, fertilizers, and mechanization) and input substitution. The AP-CSAPs considered in this research included zero/minimum tillage, rotational cropping, green manuring, organic manuring, residue retention, and agroforestry. The authors employed the seemingly unrelated regression method to estimate data collected from 1,500 smallholder rice farmers in Nigeria. The authors found that labour and fertilizer were not easily substitutable in the Nigerian context; increases in the unit price of labour (wage rate) and fertilizer lead to a greater budget allocation towards these inputs. Conversely, a rise in the cost of mechanization services per hectare significantly reduced labour costs while increasing expenditure on pesticides and mechanization services. They also found that most AP-CSAPs were labour-intensive, except for agroforestry, which is labor-neutral. Organic manure and residue retention notably conserved pesticides, whereas zero/minimum tillage practices increased the use of pesticides and fertilizers. Furthermore, the demand for most production factors, except pesticides, was found to be price inelastic, indicating that price changes do not significantly alter the quantity demanded.

4.3 Progress of research on CSA

Understanding the progress of research on CSA is essential for identifying and leveraging technological innovations—like greenhouse advancements, organic fertilizer products, and biotechnological crop improvements—that support sustainable agricultural adaptation. This knowledge enables the integration of nature-based strategies, informs policy, and underscores the importance of international cooperation in overcoming patent and CSA adoption challenges to ensure global food security amidst climate change. We collected one paper in this field.

Tey, Brindal, Darham and Zainalabidin's paper, "*Adaptation technologies for climate-smart agriculture: A patent network analysis*", delved into the advancements in technological innovation for agricultural adaptation within the context of CSA by analyzing global patent databases. The authors found that greenhouse technologies have seen a surge in research and development (R&D) efforts, whereas composting technologies have evolved into innovations in organic fertilizer products. Additionally, biotechnology has been a significant focus, aiming to develop crop traits better suited to changing climate conditions. A notable emergence is seen in resource restoration innovations addressing climate challenges. These technologies offer a range of policy options for climate-smart agriculture, from broad strategies to specific operational techniques, and pave the way for integration with nature-based adaptation strategies. However, the widespread adoption and potential impact of these technologies may be hindered by issues related to patent ownership and the path dependency this creates. Despite commercial interests driving the diffusion of innovation, international cooperation is clearly needed to enhance technology transfer.

5 Summary of key policy implications

The collection of 19 papers in this special issue sheds light on the critical aspects of promoting farmers' adoption of CSA practices, which eventually help enhance agricultural productivity and resilience, reduce greenhouse gas emissions, improve food security and soil health, offer economic benefits to farmers, and contribute to sustainable development and climate change adaptation. We summarize and discuss the policy implications derived from this special issue from the following four aspects:

5.1 Improving CSA adoption through extension services

Extension services help reduce information asymmetry associated with CSA adoption and increase farmers' awareness of CSA practices' benefits, costs, and risks while addressing their specific challenges. Therefore, the government should improve farmers' access to extension services. These services need to be inclusive and customized to meet the gender-specific needs and the diverse requirements of various farming stakeholders. Additionally, fostering partnerships between small and medium enterprises and agricultural extension agents is crucial for enhancing the local availability of CSA technologies. Government-sponsored extension services should prioritize equipping farmers with essential CSA skills, ensuring they are well-prepared to implement these practices. This structured approach will streamline the adoption process and significantly improve the effectiveness of CSA initiatives.

5.2 Facilitating CSA adoption through farmers' organizations

Farmers' organizations, such as village cooperatives, farmer groups, and self-help groups, play a pivotal role in facilitating farmers' CSA adoption and empowering rural women's adoption through effective information dissemination and the use of agricultural apps. Therefore, the government should facilitate the establishment and development of farmers' organizations and encourage farmers to join those organizations as members. In particular, the proven positive impacts of farmer-based organizations (FBOs) highlight the importance of fostering collaborations between governments and FBOs. Supporting farmer cooperatives with government financial and technical aid is essential for catalyzing community-driven climate adaptation efforts. Furthermore, the successful use of DAS in promoting CSA adoption underscores the need for government collaboration with farmer groups to expand DAS utilization. This includes overcoming usage barriers and emphasizing DAS's reliability as a source of climate-smart information. By establishing and expanding digital hubs and demonstration centres in rural areas, farmers can access and experience DAS technologies firsthand, leading to broader adoption and integration into their CSA practices.

5.3 Enhancing CSA adoption through agricultural training and education

Agricultural training and education are essential in enhancing farmers' adoption of CSA. To effectively extend the reach of CSA practices, the government should prioritize expanding rural ICT infrastructure investments and establish CSA training centres equipped with ICT tools that target key demographics such as women and older people, aiming to bridge the digital adoption gaps. Further efforts should prioritize awareness and training programs to ensure farmers can access weather and agro-advisory services. These programs should promote the use of ICT-based tools through collaborations with technology providers and include regular CSA training and the establishment of demonstration fields that showcase the tangible benefits of CSA practices.

Education plays a vital role in adopting CAPs, suggesting targeted interventions such as comprehensive technical training to assist farmers with limited educational backgrounds in understanding the value of CAPs, ultimately improving their adoption rates. Establishing robust monitoring mechanisms is crucial to maintaining farmer engagement and success in CSA practices. These mechanisms will facilitate the ongoing adoption and evaluation of CSA practices and help educate farmers on the long-term benefits. Centralizing and disseminating information about financial products and subsidies through various channels, including digital platforms tailored to local languages and contexts, is essential. This approach helps educate farmers on financing options and requirements, supporting the adoption of CSA technologies among smallholder farmers. Lastly, integrating traditional and local knowledge with scientific research and development can effectively tailor CSA initiatives. This integration requires the involvement of a range of stakeholders, including NGOs, to navigate the complexities of CSA and ensure that interventions are effective but also equitable and sustainable. The enhanced capacity of institutions and their extension teams will further support these CSA initiatives.

5.4 Promoting CSA adoption through establishing social networks and innovating strategies

The finding that social networks play a crucial role in promoting the adoption of CSA suggests that implementing reward systems to incentivize current CSA adopters to advocate for climate-smart practices within their social circles could be an effective strategy to promote CSA among farmers. The evidence of a significant link between family farms' awareness of social responsibility and their adoption of CSA highlights that governments should undertake initiatives, such as employing lectures and pamphlets, to enhance family farm operating farmers' understanding of social responsibility. The government should consider introducing incentives that foster positive behavioural changes among family farms to cultivate a more profound commitment to social responsibility. The government can also consider integrating social responsibility criteria into the family farm awards and recognition evaluation process. These measures would encourage family farms to align their operations with broader social and environmental goals, promoting CSA practices.

Combining traditional incentives, such as higher wages and access to improved agricultural inputs, with innovative strategies like community-driven development for equipment sharing and integrating moral suasion with Payment for Ecosystem Services would foster farmers' commitment to CSA practices. The finding that technological evolution plays a vital role in shaping adaptation strategies for CSA highlights the necessity for policy instruments that not only leverage modern technologies but also integrate them with traditional, nature-based adaptation strategies, enhancing their capacity to address specific CSA challenges. Policymakers should consider the region's unique socioeconomic, environmental, and geographical characteristics when promoting CSA, moving away from a one-size-fits-all approach to ensure the adaptability and relevance of CSA practices across different agricultural landscapes. They should foster an environment that encourages the reporting of all research outcomes to develop evidence-based policies that are informed by a balanced view of CSA's potential benefits and limitations.

Finally, governance is critical in creating an enabling environment for CSA adoption. Policies should support CSA practices and integrate environmental sustainability to enhance productivity and ecosystem health. Development programs must offer financial incentives, establish well-supported voluntary schemes, provide robust training programs, and ensure the wide dissemination of informational tools. These measures are designed to help farmers integrate CAPs into their operations, improving economic and operational sustainability.

6 Concluding remarks

This special issue has provided a wealth of insights into the adoption and impact of CSA practices across various contexts, underscoring the complexity and multifaceted nature of CSA implementation. The 19 papers in this special issue collectively emphasize the importance of understanding local conditions, farmer characteristics, and broader socioeconomic and institutional factors that influence CSA adoption. They highlight the crucial role of extension services, digital advisory services, social responsibility awareness, and diverse forms of capital in facilitating the adoption of CSA practices. Moreover, the findings stress the positive impact of CSA on farm productivity, income diversification, and resilience to climate change while also pointing out the potential for CSA practices to address broader sustainability goals.

Significantly, the discussions underline the need for policy frameworks that are supportive and adaptive, tailored to specific regional and local contexts to promote CSA adoption effectively. Leveraging social networks, enhancing access to financial products and mechanisms, and integrating technological innovations with traditional agricultural practices are vital strategies for scaling CSA adoption. Furthermore, the discussions advocate for a balanced approach that combines economic incentives with moral persuasion and community engagement to foster sustainable agricultural practices.

These comprehensive insights call for concerted efforts from policymakers, researchers, extension agents, and the agricultural community to foster an enabling environment for CSA. Such an environment would support knowledge exchange, financial accessibility, and the adoption of CSA practices that contribute to the resilience and sustainability of agricultural systems in the face of climate change. As CSA continues to evolve, future research should focus on addressing the gaps identified, exploring innovative financing and technology dissemination models, and assessing the long-term impacts of CSA practices on agricultural sustainability and food security. This special issue lays the groundwork for further exploration and implementation of CSA practices, aiming to achieve resilient, productive, and sustainable agricultural systems worldwide and contribute to the achievements of the United Nations Sustainable Development Goals.

Appendix

Table 1 A summary of the 19 papers included in the special issue

Number	Authors	Titles	Study area	CSA technologies
1	Li, Ma and Zhu	A systematic literature review of factors influencing the adoption of climate-smart agricultural practices	International	Literature review [a]
2	Thottadi and Singh	Climate-smart agriculture (CSA) adaptation, adaptation determinants and extension services synergies: A systematic review	India	Literature review
3	Naveen, Datta, Behera and Rahut's	Climate-Smart Agriculture in South Asia: Exploring Practices, Determinants, and Contribution to Sustainable Development Goals	South Asia	Literature review
4	Wang, Wang and Fu	Can social networks facilitate smallholders' decisions to adopt Climate-smart Agriculture technologies? A three-level meta-analysis	International	Meta-analysis [b]
5	Sandilya and Goswami	Effect of different forms of capital on the adoption of multiple climate-smart agriculture strategies by smallholder farmers in Assam, India	India	Crop diversification; Site-specific nutrient management; Integrated nutrient management; Alternate land use system
6	Ye, Zhang, Song and Li	Social Responsibility Awareness and Adoption of Climate-smart Agricultural Practices: Evidence from Food-based Family Farms in China	China	Soil testing; Fertilization techniques; No-till means
7	Asante, Ma, Prah and Temoso	Promoting the adoption of climate-smart agricultural technologies among maize farmers in Ghana: using digital advisory services	Ghana	Row planting; Zero tillage; Drought-tolerant seeds
8	Villalba, Joshi, Daum and Venus	Financing Climate-Smart Agriculture: A Case Study from the Indo-Gangetic Plains	India	Laser land levelers; Happy seeders
9	Mburu, Mburu, Nyikal, Mugera and Ndambi	Distributional impact of climate smart villages on access to savings and credit and adoption of improved climate-smart agricultural practices in the Nyando Basin, Kenya	Kenya	Improved livestock breeds; Improved sheep and goats

Table 1 (continued)

Number	Authors	Titles	Study area	CSA technologies
10	Davila, Jacobs, Nadeem, Kelly and Kurimoto	Finding climate smart agriculture in civil-society initiatives	East Africa, South and Southeast Asia	Rainwater harvesting; Agroforestry; On-farm Farmer Managed Natural Regeneration; soil conservation; and fertility enhancement; Small-scale irrigation
11	Zheng, Ma and He	Climate-smart agricultural practices for enhanced farm productivity, income, resilience, and greenhouse gas mitigation: A Comprehensive Review	International	Literature review
12	Tanti, Jena, Timilsina and Rahut	Enhancing crop yields and farm income through climate-smart agricultural practices in Eastern India	India	Crop rotation; Integrated soil management;
13	Asante, Ma, Prah and Temoso	Farmers' adoption of multiple climate-smart agricultural technologies in Ghana: Determinants and impacts on maize yields and net farm income	Ghana	Zero tillage; Row planting; Drought-resistant seed
14	Mburu, Mburu, Nyikal, Mugera and Ndambi	Assessment of Socioeconomic Determinants and Impacts of Climate-Smart Feeding Practices in the Kenyan Dairy Sector	Kenya	Climate-smart fodder; Climate-smart feed concentrates
15	Singh, Bisaria, Sinha, Patasaraiya and Sreerag	Developing A Composite Weighted Indicator-based Index for Monitoring and Evaluating Climate-Smart Agriculture in India	India	Many (see paper)
16	Sang, Chen, Hu and Rahut	Economic benefits of climate-smart agricultural practices: empirical investigations and policy implications	China	Water-saving irrigation; Organic fertilizer; Farmyard manure; Zero tillage; Fallow cropping; Crop rotation; Crop straw mulch

Table 1 (continued)

Number	Authors	Titles	Study area	CSA technologies
17	Kandulu, Zuo, Wheeler, Dusingizimana and Chagund	Influence of climate-smart technologies on the success of livestock donation programs for smallholder farmers in Rwanda	Rwanda	Cowsheds; Biogas plants
18	Kehinde, Shittu, Awe and Ajayi	Effects of Using Climate-Smart Agricultural Practices on Factor Demand and Input Substitution among Smallholder Rice Farmers in Nigeria	Nigeria	Zero/minimum tillage; Rotational cropping; Green manuring; Organic manuring; Residue retention; Agroforestry
19	Tey, Brindal, Darham and Zainaladin	Adaptation technologies for climate-smart agriculture: A patent network analysis	International	Greenhouse technologies; Organic fertilizer; Biotechnology

[a, b] The literature review and meta-analysis studies involve many CSA practices and technologies. Thus, they were not listed in the table to save space

Acknowledgements We want to thank all the authors who have submitted papers for the special issue and the reviewers who reviewed manuscripts on time. We acknowledge the Asian Development Bank Institute (ADBI) for supporting the virtual international conference on "*Climate-smart Agriculture: Adoption, Impacts, and Implications for Sustainable Development*" held on 10-11 October 2023. Special thanks to the invited keynote speakers, Prof. Edward Barbier and Prof. Tatsuyoshi Saijo. Finally, we would like to express our thanks, gratitude, and appreciation to the session chairs (Prof. Anita Wreford, Prof. Jianjun Tang, Prof. Alan Renwick, and Assoc. Prof. Sukanya Das), ADBI supporting team (Panharoth Chhay, Mami Nomoto, Mami Yoshida, and Raja Rajendra Timilsina), and discussants who made substantial contributions to the conference.

Funding Open Access funding enabled and organized by CAUL and its Member Institutions

Data availability No new data were created or analyzed during this study. Data sharing is not applicable to this article.

Declarations

Conflict of interests The authors declare no known interests related to their submitted manuscript.

References

Akter A, Geng X, EndelaniMwalupaso G et al (2022) Income and yield effects of climate-smart agriculture (CSA) adoption in flood prone areas of Bangladesh: farm level evidence. Clim Risk Manag 37:100455. https://doi.org/10.1016/j.crm.2022.100455

Alam MF, Sikka AK (2019) Prioritizing land and water interventions for climate-smart villages. Irrig Drain 68:714–728. https://doi.org/10.1002/ird.2366

Amadu FO, McNamara PE, Miller DC (2020) Yield effects of climate-smart agriculture aid investment in southern Malawi. Food Policy 92:101869. https://doi.org/10.1016/j.foodpol.2020.101869

Arora NK (2019) Impact of climate change on agriculture production and its sustainable solutions. Environ Sustain 2:95–96. https://doi.org/10.1007/s42398-019-00078-w

Aryal JP, Rahut DB, Maharjan S, Erenstein O (2018) Factors affecting the adoption of multiple climate-smart agricultural practices in the Indo-Gangetic Plains of India. Nat Resour Forum 42:141–158. https://doi.org/10.1111/1477-8947.12152

Aryal JP, Farnworth CR, Khurana R et al (2020a) Does women's participation in agricultural technology adoption decisions affect the adoption of climate-smart agriculture? Insights from Indo-Gangetic Plains of India. Rev Dev Econ 24:973–990. https://doi.org/10.1111/rode.12670

Aryal JP, Rahut DB, Sapkota TB et al (2020b) Climate change mitigation options among farmers in South Asia. Environ Dev Sustain 22:3267–3289. https://doi.org/10.1007/s10668-019-00345-0

Belay AD, Kebede WM, Golla SY (2023) Determinants of climate-smart agricultural practices in smallholder plots: evidence from Wadla district, northeast Ethiopia. Int J Clim Chang Strateg Manag. https://doi.org/10.1108/IJCCSM-06-2022-0071

Brown T (2016) Civil society organizations for sustainable agriculture: negotiating power relations for pro-poor development in India. Agroecol Sustain Food Syst 40:381–404. https://doi.org/10.1080/21683565.2016.1139648

Diro S, Tesfaye A, Erko B (2022) Determinants of adoption of climate-smart agricultural technologies and practices in the coffee-based farming system of Ethiopia. Agric Food Secur 11:1–14. https://doi.org/10.1186/s40066-022-00385-2

FAO (2013) Climate smart agriculture sourcebook. Food and agriculture organization of the United Nations

García de Jalón S, Silvestri S, Barnes AP (2017) The potential for adoption of climate smart agricultural practices in Sub-Saharan livestock systems. Reg Environ Chang 17:399–410. https://doi.org/10.1007/s10113-016-1026-z

Hariharan VK, Mittal S, Rai M et al (2020) Does climate-smart village approach influence gender equality in farming households? A case of two contrasting ecologies in India. Clim Chang 158:77–90. https://doi.org/10.1007/s10584-018-2321-0

Israel MA, Amikuzuno J, Danso-Abbeam G (2020) Assessing farmers' contribution to greenhouse gas emission and the impact of adopting climate-smart agriculture on mitigation. Ecol Process 9. https://doi.org/10.1186/s13717-020-00249-2

Jamil I, Jun W, Mughal B et al (2021) Does the adaptation of climate-smart agricultural practices increase farmers' resilience to climate change? Environ Sci Pollut Res 28:27238–27249. https://doi.org/10.1007/s11356-021-12425-8

Kang Y, Khan S, Ma X (2009) Climate change impacts on crop yield, crop water productivity and food security - a review. Prog Nat Sci 19:1665–1674. https://doi.org/10.1016/j.pnsc.2009.08.001

Kangogo D, Dentoni D, Bijman J (2021) Adoption of climate-smart agriculture among smallholder farmers: does farmer entrepreneurship matter? Land Use Policy 109:105666. https://doi.org/10.1016/j.landusepol.2021.105666

Keil A, Krishnapriya PP, Mitra A et al (2021) Changing agricultural stubble burning practices in the Indo-Gangetic plains: is the Happy Seeder a profitable alternative? Int J Agric Sustain 19:128–151. https://doi.org/10.1080/14735903.2020.1834277

Khatri-Chhetri A, Regmi PP, Chanana N, Aggarwal PK (2020) Potential of climate-smart agriculture in reducing women farmers' drudgery in high climatic risk areas. Clim Chang 158:29–42. https://doi.org/10.1007/s10584-018-2350-8

Kifle T, Ayal DY, Mulugeta M (2022) Factors influencing farmers adoption of climate smart agriculture to respond climate variability in Siyadebrina Wayu District, Central Highland of Ethiopia. Clim Serv 26:100290. https://doi.org/10.1016/j.cliser.2022.100290

Kpadonou RAB, Owiyo T, Barbier B et al (2017) Advancing climate-smart-agriculture in developing drylands: joint analysis of the adoption of multiple on-farm soil and water conservation technologies in West African Sahel. Land Use Policy 61:196–207. https://doi.org/10.1016/j.landusepol.2016.10.050

Läderach P, Ramirez-Villegas J, Navarro-Racines C et al (2017) Climate change adaptation of coffee production in space and time. Clim Chang 141:47–62. https://doi.org/10.1007/s10584-016-1788-9

Makate C, Makate M, Mango N, Siziba S (2019) Increasing resilience of smallholder farmers to climate change through multiple adoption of proven climate-smart agriculture innovations. Lessons from Southern Africa. J Environ Manag 231:858–868. https://doi.org/10.1016/j.jenvman.2018.10.069

Martey E, Etwire PM, Mockshell J (2021) Climate-smart cowpea adoption and welfare effects of comprehensive agricultural training programs. Technol Soc 64:101468. https://doi.org/10.1016/j.techsoc.2020.101468

McNunn G, Karlen DL, Salas W et al (2020) Climate smart agriculture opportunities for mitigating soil greenhouse gas emissions across the U.S. corn-belt. J Clean Prod 268:122240. https://doi.org/10.1016/j.jclepro.2020.122240

Mirón IJ, Linares C, Díaz J (2023) The influence of climate change on food production and food safety. Environ Res 216:114674. https://doi.org/10.1016/j.envres.2022.114674

Omotoso AB, Omotayo AO (2024) Enhancing dietary diversity and food security through the adoption of climate-smart agricultural practices in Nigeria: a micro level evidence. Environ Dev Sustain. https://doi.org/10.1007/s10668-024-04681-8

Radeny M, Rao EJO, Ogada MJ et al (2022) Impacts of climate-smart crop varieties and livestock breeds on the food security of smallholder farmers in Kenya. Food Secur 14:1511–1535. https://doi.org/10.1007/s12571-022-01307-7

Santalucia S (2023) Nourishing the farms , nourishing the plates : association of climate - smart agricultural practices with household dietary diversity and food security in smallholders. 1–21. https://doi.org/10.1002/agr.21892

Shikuku KM, Valdivia RO, Paul BK et al (2017) Prioritizing climate-smart livestock technologies in rural Tanzania: a minimum data approach. Agric Syst 151:204–216. https://doi.org/10.1016/j.agsy.2016.06.004

Tabe-Ojong MP, Aihounton GBD, Lokossou JC (2023) Climate-smart agriculture and food security: cross-country evidence from West Africa. Glob Environ Chang 81:102697. https://doi.org/10.1016/j.gloenvcha.2023.102697

Tran NLD, Rañola RF, Ole Sander B et al (2020) Determinants of adoption of climate-smart agriculture technologies in rice production in Vietnam. Int J Clim Chang Strateg Manag 12:238–256. https://doi.org/10.1108/IJCCSM-01-2019-0003

United Nations (2021) Economic and social council: population, food security, nutrition and sustainable development. Oxford Handb United Nations 1–20. https://www.un.org/development/desa/pd/sites/www.un.org.development.desa.pd/files/undesa_pd_2021_e_cn.9_2021_2_advanceunedited.pdf. Accessed 1 Feb 2024

Vatsa P, Ma W, Zheng H, Li J (2023) Climate-smart agricultural practices for promoting sustainable agrifood production: yield impacts and implications for food security. Food Policy 121:102551. https://doi.org/10.1016/j.foodpol.2023.102551

Waaswa A, OywayaNkurumwa A, MwangiKibe A, NgenoKipkemoi J (2022) Climate-Smart agriculture and potato production in Kenya: review of the determinants of practice. Clim Dev 14:75–90. https://doi.org/10.1080/17565529.2021.1885336

Waters-Bayer A, Kristjanson P, Wettasinha C et al (2015) Exploring the impact of farmer-led research supported by civil society organizations. Agric Food Secur 4:1–7. https://doi.org/10.1186/s40066-015-0023-7

Zakaria A, Azumah SB, Appiah-Twumasi M, Dagunga G (2020) Adoption of climate-smart agricultural practices among farm households in Ghana: the role of farmer participation in training programmes. Technol Soc 63:101338. https://doi.org/10.1016/j.techsoc.2020.101338

Zhou X, Ma W, Zheng H et al (2023) Promoting banana farmers' adoption of climate-smart agricultural practices: the role of agricultural cooperatives. Clim Dev:1–10. https://doi.org/10.1080/17565529.2023.2218333

Zizinga A, Mwanjalolo J-GM, Tietjen B et al (2022) Climate change and maize productivity in Uganda: simulating the impacts and alleviation with climate smart agriculture practices. Agric Syst 199:103407. https://doi.org/10.1016/j.agsy.2022.103407

Authors and Affiliations

Wanglin Ma[1] · Dil Bahadur Rahut[2]

✉ Wanglin Ma
Wanglin.Ma@lincoln.ac.nz

Dil Bahadur Rahut
drahut@adbi.org

1 Department of Global Value Chains and Trade, Faculty of Agribusiness and Commerce, Lincoln University, Christchurch, New Zealand

2 Asian Development Bank Institute, Tokyo, Japan