Journal of Agriculture and Rural Development in the Tropics and Subtropics
Vol. 126 No. 1 (2025) 25–42

https://doi.org/10.17170/kobra-2025011410816 ISSN: 2363-6033 (online); 1612-9830 (print) – website: www.jarts.info

A review of climate-smart agriculture in Asia: Critical achievements, key challenges, and potential prospects

Hang Thi Thuy Nguyen*, Thi Quynh Anh Le, Mai Chiem Tuyen, Pham Xuan Hung

Faculty of Economics and Development Studies, University of Economics, Hue University, Hue City, Vietnam

Abstract

Climate change is posing a risk to rural communities and smallholders in Asia, whose livelihoods traditionally depend on farming. To address this, climate-smart agriculture (CSA) is widely encouraged for sustainable development. Despite global recognition of CSA, there is currently limited evidence to generalise and evaluate the practical implementation of CSA in this region. Given various agro-climate conditions, institutional settings, and socioeconomic backgrounds, this paper conducted a systematic review of the achievements, challenges, and prospects of CSA in Asian countries. We classified nine groups of CSA practices: conservation agriculture, water management, climate-resilient varieties, agricultural diversification, integrated pest management, nutrient management, precision farming, agrivoltaics, and livestock management. The linkages of enabling policies, knowledge transfer, market conditions, financial mechanisms, and socioeconomic background are crucial in supporting the performance and sustainability of CSA. In addition to the achievements in distinct criteria (productivity, adaptation, and mitigation), key challenges include the lack of enforcing guidelines, the shortage of learning platforms, the limitation of financial support, and the weakness of coordination among partnerships in the long term. To promote CSA in Asia, the engagement of multi-stakeholders at multi-levels should be increased to enhance the capacities of farming households and help them adopt responsive actions to local conditions.

Keywords: adaptation, climate change, mitigation, productivity, sustainable agriculture, systematic review

1 Introduction

The conceptual and practical efforts of climate-smart agriculture (CSA) have gradually been identified as a way to improve the integration of agricultural development and climate resilience in the context of growing concerns about climate change and greenhouse gas (GHG) emissions in Asia. The adverse effects of climate change tend to be apparent across different production systems and agroecological zones (Bhatt *et al.*, 2019a). Declined underground water, deteriorated soil structure, and increased pest and disease incidence, associated with the typical frequency and intensity of droughts, salinity, heavy rainfalls, and heat waves of Asian climates have widely resulted in greater instability and insecurity of food production (Lipper *et al.*, 2014, Bhatt *et al.*, 2019a). These consequences have threatened rural communities, especially socially disadvantaged groups or vulnerable marginal households whose livelihoods primarily depend on agriculture. Simultaneously, agriculture is also a considerable contributor to GHG, and substantial growth in agricultural production has come at a significant environmental cost. Inappropriate land use and significant emission sources derived from improper soil management, agrochemicals application, livestock manure, and biomass burning have considerably accumulated air pollution, which led to the crucial request of using production resources efficiently and sustainably, especially land, water, and energy toward sustainable development.

Proposed by FAO (2010, 2013), CSA has been designed to address three critical criteria: i) sustainably increase agricultural productivity to support equitable increases in incomes, food security and development; ii) adapt and build resilience to climate change; and iii) reduce GHG emissions in agriculture compared to conventional trends (Pye-Smith, 2011; Lipper *et al.*, 2014; Sova *et al.*, 2018; Hussain *et al.*,

* Corresponding author: nguyenthithuyhang_dhkt@hueuni.edu.vn

Published online: 6 February 2025 – Received: 12 April 2024 – Accepted: 29 January 2025

2022). Various CSA practices have been globally and locally applied to increase farm productivity, adapt to climatic variability, and/or minimise the emission of GHGs from agroecosystems to the environment. Depending on various policies and strategies of each country, CSA practices and technologies have generally combined indigenous farming knowledge based on accumulated experiences of farmers in the face of climate variability and production risks, and advanced agricultural innovations that allow sustainable conservation of production resources and improved productivity and livelihoods. CSA should not be considered universally applicable in Asia, as CSA technologies and practices are frequently location-specific and tailored to fit the specific agroecological and socioeconomic conditions (Thornton *et al.*, 2018).

This review study focuses on Asia for three key reasons. First, as the largest continent with diverse topographic features, Asia is home to various agroecological zones and different production systems. Second, Asia is recognised as one of the most vulnerable regions to global climate change, where agricultural production faces significant challenges due to increased GHG concentrations (Bhatt *et al.*, 2019b). A comprehensive review of CSA in this region can provide a clear understanding of the achievements, challenges, and future directions of CSA in the efforts to cope with these issues (Raihan *et al.*, 2024). Third, Asia encompasses a wide range of socioeconomic backgrounds among agricultural producers. An in-depth exploration of CSA in Asia promotes to sharing experiences, from traditional indigenous practices to advanced technological applications, which can be tailored and replicated in other regions through the involvement of multiple stakeholders (Chandra *et al.*, 2018).

Although the benefits of CSA have been clearly defined and CSA has been well-targeted from the conceptual framework and policy initiatives, real uptake of CSA has remained slow, spontaneous, and fragmented among farming villages in Asian countries (Sova *et al.*, 2018; Nguyen *et al.*, 2017). Numerous studies have acquired CSA technologies and practices as merely pilot programs and found it challenging to scale up due to certain restrictions. While there is currently scant evidence to generalise and evaluate the practical implementation of CSA in this region, a comprehensive assessment of CSA in Asian countries is crucial to provide informed insights for policymakers and stakeholders to drive the sustainability of CSA in the long term. As a result, based on a thorough review of related research results and reports of reputable journals and organisations, this paper aims to provide a systematic evaluation of CSA in Asia by briefly describing CSA technologies and practices primarily adopted in Asian countries, identifying the enabling factors associated with the performance of CSA, concluding remarkable achievements and challenges before drawing policy implications for prospects of CSA development pathway.

2 Data and methodology

Our study is based on seven assessed benefits/criteria of CSA practices as mentioned in the Climate-smart Agriculture Sourcebook by FAO (2013) to select and classify CSA practices. These include (1) reduced soil erosion and improved nitrogen efficiency from rotation, cover and minimum/zero tillage activities; (2) improved water availability from soil and water conservation activities; (3) improved crop yield by adopting new or improved varieties and changing in farm management; (4) improved livestock productivity through changes in livestock management such as enhanced breeding and feeding practices; (5) improved productivity, market prices, and farm income through fertiliser subsidy programmes or nutrient management; (6) improved economic resilience from income diversification; and (7) reduced GHG emissions through better management practices. These assessed benefits/criteria serve as the foundation for the classification of seven groups of CSA in our study, including (i) conservation agriculture, (ii) agriculture water management strategies, (iii) climate-resilient crop varieties/ improved varieties, (iv) agricultural diversification, (v) integrated pest management, (vi) nutrient management, and (vii) livestock management. Moreover, during our literature synthesis process of CSA in Asia, we noticed that precision agriculture and agrivoltaics practices are considered CSA practices and have been adopted in some Asian countries in recent years. Therefore, our study incorporated two groups (precision agriculture and agrivoltaics) into the classification of CSA in Asia.

This study employs a systematic literature review method to explore the critical achievements, key challenges, and potential prospects of CSA implementation in Asia (Tawfik *et al.*, 2019). To ensure the relevance and impartiality of the collected data, several approaches and insights from methodical manual searches were applied (Vassar *et al.*, 2016). A range of inclusion criteria and organised steps were implemented to conduct a methodical manual search. Relevant English-language references, primarily consisting of research studies, review papers and book chapters, were carefully selected and synthesised from respected academic databases, such as Web of Science, Scopus, ScienceDirect and Google Scholar. In addition, supplementary materials from reliable reports issued by international and regional organisations were also utilised. Based on the classification of CSA practices as mentioned above, we utilised the manual search through an online database search using a variety of keywords and search terms, including "climate-smart agriculture", "productivity", "adaptation", "mitigation", "achievements", "challenges", "conservation agriculture", "water management", "climate-resilient varieties", "agricultural diversification", "integrated pest management", "nutrient management", "precision farming", "agrivoltaics", and "livestock management" that were specifically focused in Asia or certain Asian countries. Moreover, our study employed the Boolean search method by combining keywords or search terms. We conducted searches by combining the search keyword "climate-smart agriculture" with other keywords, such as (1) "climate-smart agriculture" AND "productivity" OR "adaptation" OR "mitigation", (2) "climate-smart agriculture" AND "achievements", (3) "climate-smart agriculture" AND "challenges", (4) "climate-smart agriculture" AND – nine CSA groups as listed above. To guarantee the quality and reliability of the findings, we included research articles published in peer-reviewed journals. The secondary literature on CSA, including supplementary materials from reliable reports, was also reviewed. As our review focuses on recent results in CSA, references published from 2005 to 2024 were prioritised for selection. Following this, we conducted a data verification procedure to re-examine the completeness (abstract availability, sufficient text), relevance, and non-duplication of the topics and contents. Ultimately, we refined and selected 102 references for this study.

This literature list was then organised and analysed based on specific issues of interest, using the insights from the constant comparison method (Strauss, 1987) and content analysis (Krippendorff, 2018; Patton, 2002; Weber, 1990). The content analysis method allowed us to examine the concepts and patterns systematically, and it was used throughout the process of synthesising and categorising literature. In addition, one of the most frequent uses of the content analysis method is to ascertain trends in the research content by content analysing the discipline journal articles. Following this method, the literature sources were grouped into categories including CSA technologies and practices, achievements of CSA, and challenges for CSA adoption. Then, these categories were further divided into subcategories. The subcategories of CSA technologies and practices consist of nine groups of CSA practices as mentioned. Each CSA group is then analysed to identify adoption trends in specific Asian countries. The subcategories of CSA's achievements were classified based on the findings reported in literature according to three pillars of CSA (1) productivity, (2) mitigation, and (3) adaptation. Regarding the challenges, we identify and outline the trend of challenges in adopting CSA in Asian countries; and then group them into six key issues, including enforcing mechanisms, financial support, household capacity, technology diffusion, infrastructure, and climate change. In addition, the trend of each key challenge happening in certain Asian countries is identified. Each subcategory of all categories had specific relevant patterns. These categories, subcategories, and patterns were derived directly from the data. The constant comparison method helped us structurally sort and organise raw ideas to formulate new insights. This method was applied to develop new categories, subcategories, and patterns until data saturation was reached. In our study, the method of constant comparison was utilised to develop new subcategories by adding two groups/subcategories - precision agriculture and agrivoltaics - into the existing classification CSA practices. Finally, these categories, subcategories and patterns were visualised by using table templates to ensure consistency.

3 Overview of CSA technologies and practices in Asia

The growing interest and support for sustainable agriculture has promoted the adoption of CSA technologies and practices among farmers in Asian countries. In recent years, farmers have been applying various agricultural technologies to improve their adaptive capacity to climate change and enhance their income. The adoption of CSA practices varies by the types and characteristics of agricultural production in specific local contexts. Based on the reviewed literature, CSA technologies and practices in Asia are classified into nine groups (Table 1).

Conservation agriculture (CA)

CA is a common farming system that supports sustainable land management. CA consists of three core principles: (i) minimum soil disturbance through minimising or no tillage or direct seeding; (ii) maintenance of soil cover through mulching or crop cover, and (iii) cropping diversity including crop rotation. The use of CA practices has contributed to preventing soil erosion and degradation, restoring soil fertility and adapting to climate change (Legoupil *et al.*, 2015; FAO, 2013). CA practices have been adopted in many countries in Asia, commonly in South Asia (Pakistan, India, Bhutan, Nepal, Sri Lanka, Bangladesh) and Southeast Asia (Vietnam, Philippines, Indonesia). CA practices in Asian countries are quite diverse and abundant, including zero or minimum or reduced tillage; the combination of no-tillage, recommended dose of fertiliser, residue management; mulch or cover crop; ridge planting system; intercropping; ratoon management; and dry sowing (Table 1).

Table 1: *Climate smart agriculture (CSA) technologies and practices primarily adopted in Asian countries.*

Major groups of CSA technologies and practices	*Detailed CSA technologies and practices*	*Countries*	*References*
Conservation agriculture	- Zero/minimum/reduced tillage - Combination of no tillage, recommended dose of fertiliser, and residue management. - Sustainable land management - Mulch/cover crop - Ridge planting system - Intercropping - Ratoon management (minimum soil disturbance) - Dry sowing	Pakistan, India, Vietnam, Bangladesh, Bhutan, Nepal, Sri Lanka, Philippines, Indonesia, The Kyrgyz Rep.	Sardar *et al.* (2021); Aryal *et al.* (2018); Kakraliya *et al.* (2021); Hasan *et al.* (2018); Dikitanan *et al.* (2017), CIAT & World Bank. (2017a, 2017b, 2018); CIAT *et al.* (2017); Nguyen *et al.* (2017); World Bank & CIAT (2015); Savelli *et al.* (2021).
Agriculture water management strategies	- System of rice intensification (SRI) - Alternate wetting and drying (AWD) - Bunds/terraces - Laser land levelling - Raising crops on bed - Conjunctive use of water - Drainage management - Water saving irrigation - Contour farming - Planting in fish scale pits - Solar-powered irrigation - Direct seeding - Sorjan cultivation method - Floating bed cultivation on water bodies - Irrigation at critical time (solar-based) - Micro irrigation (drip irrigation, sprinkle) - Water efficient irrigation (ridge and furrow, flat bed in dry) - Regulated deficit irrigation - Bubbler irrigation - Water collection tube system	Vietnam, Philippines, Pakistan, India, Bangladesh, Bhutan, Nepal, Sri Lanka, Indonesia, Lao, Cambodia, Thailand, Indonesia, The Kyrgyz Rep.	Ha & Van Bac (2021); Rejesus *et al.* (2011), Sardar *et al.* (2021); Aryal *et al.* (2018); Imran *et al.* (2019); Imran *et al.* (2022); Mishra *et al.* (2021); Nguyen *et al.* (2017); Hasan *et al.* (2018); Kabir *et al.* (2022); Savelli *et al.* (2021); Nguyen & Hung (2022); Dikitanan *et al.* (2017); CIAT & World Bank. (2017a, 2017b, 2017c, 2018); CIAT *et al.* (2017).
Adoption of climate-resilient crop varieties/ improved varieties	- Drought-tolerant varieties - Stress-tolerant varieties - Flood-resistant varieties - Submergence-resistant and high-yielding varieties - Short duration and high-yielding varieties - Salinity-resistant varieties - Lodging-resistant (tall) high-yielding varieties - Disease-resistant varieties - Dwarf and early-maturing varieties - Heat-tolerant varieties - Pest-resistant varieties - Certified high-quality seed - Short and ultra-short duration varieties	Vietnam, Pakistan, India, Bangladesh, Bhutan, Nepal, Indonesia, Philippines, The Kyrgyz Rep., Sri Lanka	Dung & Anh (2022); Sardar *et al.* (2021); Ha & Van Bac (2021); Lan *et al.* (2018); Aryal *et al.* (2018); Nguyen *et al.* (2017); Hasan *et al.* (2018); World Bank & CIAT (2015); Savelli *et al.* (2021); Dikitanan *et al.* (2017); CIAT & World Bank (2017a, 2017b, 2017c, 2018); CIAT *et al.* (2017).
Climate-resilient agricultural diversification	- Crop rotation - Intercropping - Rice-fish farming - Shrimp-rice farming - Crop intensification - Mixed cropping - Shrimp – forest farming - Shade trees (agroforestry) - Dairy and forestry (for fodder, forage, and fuel requirement) - Chickpea and forestry (establishment of wind barriers) - Timber-crop-livestock integration - Fruit and timber trees along with rice and vegetables	Vietnam, India, Bangladesh, Bhutan, Nepal, Pakistan, The Kyrgyz Rep., Sri Lanka, Philippines	Lan *et al.* (2018); Aryal *et al.* (2018); Nguyen *et al.* (2017); World Bank & CIAT (2015); Dikitanan *et al.* (2017); CIAT & World Bank (2017a, 2017b, 2017c, 2018); CIAT *et al.* (2017).
Integrated pest management	- Combination of tolerant varieties and removal of crop residues - Combination of organic production and disease-free seedling - Biological control - Use bio-pesticides - Organic crop protection products	Vietnam, Bhutan, Nepal, Pakistan, Indonesia, The Kyrgyz Rep.	Nguyen *et al.* (2017); Savelli *et al.* (2021); CIAT & World Bank (2017b, 2017c, 2018). CIAT *et al.* (2017).
Nutrient management	- Organic fertiliser - Micro-dosing fertiliser - Animal manure application - Site-specific nutrient management - Humus storage pits (soil's moisture increase) - Proper use of fertiliser (right timing, placement, source, amount) - Farmyard manure application and mulching - Integrated soil fertility management (organic and biological fertilisers) - Organic farming	Vietnam, Pakistan, India, Bangladesh, Bhutan, Nepal, Sri Lanka, Philippines, The Kyrgyz Rep., China, Japan, Thailand, Malaysia, East Timor, Taiwan, South Korea	Lan *et al.* (2018); Sardar *et al.* (2021); Aryal *et al.* (2018); Nguyen *et al.* (2017); World Bank & CIAT (2015); Hsieh (2005); Partap (2010); Dikitanan *et al.* (2017); CIAT & World Bank (2017a, 2017b, 2017c, 2018); CIAT *et al.* (2017).
Precision farming	- Smart Agriculture (automatic control system, apps, big data, IoT, Image recognition, Sensing & monitoring, Robotic, Drone) - Precision nutrient management (Leaf Colour Chart, Green seeker, Nutrient expert) - Precision irrigation management (right timing and amount) - Application of precise dosage of fertiliser - Laser land levelling - Leveraging artificial intelligence (AI) to tackle pink bollworm infestation for cotton - Smart irrigation for paddy fields - Precision Spraying (Treating armyworm infestation with drones)	Taiwan, Nepal, Indonesia, Pakistan, India, Vietnam, China, Japan	Chuang *et al.* (2020); CIAT *et al.* (2017); Savelli *et al.* (2021); CIAT & FAO (2018); UNDP (2021), Toriyama (2020).
Agrivoltaics	Agrophotovoltaics in rice production	Japan, South Korea, India, China	Mo *et al.* (2022); Gonocruz *et al.* (2021); Mahto *et al.* (2021), Widmer *et al.* (2024).
Livestock management	- Biogas technology - Promotion of manure compositing - Improvement of veterinary services - Fodder crop production - Improved breeds/Cross breeding (high yielding and disease-resistant breeds) - Stall feeding combined with biogas plant - Improved goat shed - Controlled shed - Automatic feeding in controlled shed - Alternative feeds	Vietnam, Bangladesh, Bhutan, Nepal, Pakistan, Sri Lanka, Indonesia, Philippines, The Kyrgyz Rep.	Nguyen *et al.* (2017); World Bank & CIAT (2015); Savelli *et al.* (2021); Dikitanan *et al.* (2017); CIAT & World Bank. (2017a, 2017b, 2017c, 2018). CIAT *et al.* (2017).

Agricultural water management strategies

Agricultural water management strategies are approaches that manage and use water resources efficiently (Chowdhury & Bajracharya, 2018). In Asia, agricultural water management strategies have been adopted under various practices with the benefits of saving water, preventing soil erosion, and using water efficiently including water surface. Almost all countries in South Asia and Southeast Asia (e.g., Vietnam, Philippines, Pakistan, India, Bangladesh, Bhutan, Nepal, Sri Lanka, Indonesia, Lao, Cambodia, Thailand, Indonesia, and the Kyrgyz Republic) applied these techniques respective to cultivation models and local contexts. Agricultural water management strategies in Asia include the System of Rice Intensification (SRI), Alternate Wetting and Drying (AWD), bunds/terraces, laser land levelling, raising crops on bed, conjunctive use of water, drainage management, water-saving irrigation, contour farming, planting in fish scale pits, solar-powered irrigation, direct seeding, sorjan cultivation method, floating bed cultivation on water bodies, irrigation at a critical time (solar-based), micro-irrigation (drip irrigation, sprinkle), water-efficient irrigation (ridge and furrow, flat bed in dry), regulated deficit irrigation, bubbler irrigation, water collection tube system (Table 1). Some practices related to CA can be grouped here (e.g., direct seeding, ridge planting systems, and contour farming) since their benefits capture both preventing soil erosion and managing water resources efficiently. We also classify some floating agriculture practices (e.g., sorjan cultivation method, floating bed cultivation on water bodies) into this group because these practices help use water resources effectively, and they can be applied in prolonged submerged areas, popularly in Bangladesh.

Adoption of climate-resilient crop varieties

The application of climate-resilient crop varieties is a critical method to help farmers adapt and cope with unpredictable weather or climate change (Acevedo *et al.*, 2020). This measure can maintain or improve crop productivity under bad weather conditions such as drought, flood, higher temperature, and salinity (Dhankher & Foyer, 2018; Saab, 2016; Acevedo *et al.*, 2020). In Asian countries, adoption of climate-resilient crop varieties is quite common in short-term food crop cultivation (e.g., rice, wheat, maize, mungbean, onion, vegetables. . .) such as drought-tolerant varieties, flood-resistant varieties, submergence-resistant and high-yielding varieties, short duration and high-yielding varieties, salinity-resistant varieties, dwarf and early-maturing varieties, heat-tolerant varieties, pest-resistant varieties, and certified high-quality seed (Table 1).

Climate-resilient agricultural diversification

Climate-resilient agricultural diversification is considered a method to ensure food security and to improve resilience to climate change. This strategy aims toward sustainable agriculture by creating benefits for the economy and environment. Agricultural diversification can be understood as a livelihood strategy that improves agricultural productivity, generates income, and reduces risks from environmental variability (Vernooy, 2022). Asian farmers have applied many ways of climate-resilient agricultural diversification, such as the cultivation of different crop species in the same space (mixed cropping, intercropping, mulching with leguminous species); rotation crop in different seasons; the combination between crop and livestock, crop and fisheries (e.g., fish, shrimp); and agroforestry (shrimp-forest farming, shade trees, dairy and forestry, timber-crop-livestock integration) (Table 1).

Integrated pest management (IPM)

IPM is an approach to pest and disease control for plants using a combination of safe and economical methods (Bajwa & Kogan, 2002; Coll & Wajnberg, 2017; Stenberg, 2017). This approach also focuses on minimising the adoption of chemical pesticides (Deguine *et al.*, 2021). The purpose of IPM is to reduce or minimise the risks to the environment and community health by integrating various pest management techniques such as regular cultivation practices with chemical and biological measures (Deguine *et al.*, 2021). Some examples of IPM techniques applied in Asian countries (e.g., Vietnam, Bhutan, Nepal, Pakistan, Indonesia, The Kyrgyz Rep. . .) are the combination of tolerant varieties and removal of crop residues, the combination of organic production and disease-free seedlings, biological control, use bio-pesticides, organic crop protection products (Table 1).

Nutrient management

Nutrient management is defined as a strategy to balance crop nutrients precisely, including organic and mineral fertilisers (WFO, IFA, & GACSA, 2017). This approach involves using efficient crop nutrients to improve agricultural productivity, decreasing the emission of nitrous oxide, and building resilience in crops (WFO, IFA, & GACSA, 2017). In Asia, nutrient management strategies are common in the following practices: the use of organic fertilisers/micro-dosing fertilisers/biological fertilisers/animal manure in crop cultivation, site-specific nutrient management, humus storage pits (soil's moisture increase), proper use of fertiliser (right timing, placement, source, and amount), and organic farming (Table 1).

Precision agriculture (PA)

PA or precision farming is a system of agricultural management that manages soil and crops to fit different conditions of each field based on information and technology (Gomiero, 2019). PA is also called "a new management technology" which comprises a set of techniques such as geographic information systems, remote sensing, Internet of things (IoT), smart farming, global positioning system (GPS), and robotics in agricultural production (Gomiero, 2019; UNDP, 2021). This approach is expected to help farmers apply the required inputs like water, fertilisers, and pesticides, in precise amounts (UNDP, 2021) to achieve higher productivity and protect crops and soil. In Asia, the adoption of PA is still relatively low compared to Europe and America, especially in developing countries that have restrictions on infrastructure and farmer's capabilities to apply high-level technology. PA in Asian countries includes smart agriculture (automatic control systems, apps, big data, IoT, Image recognition, Sensing and monitoring, Robotic, Drone) in Taiwan, precision nutrient management (Leaf Colour Chart, Green seeker, Nutrient expert), precision irrigation management (right timing and amount), application of precise dosage of fertiliser, laser land levelling in Pakistan and India, leveraging artificial intelligence (AI) to tackle pink bollworm infestation for cotton in India, smart irrigation for paddy fields in Vietnam, precision spraying (Treating armyworm infestation with drones) in China, and information and communication technology (ICT) or smart agriculture in Japan (Table 1).

Agrivoltaics

Agrivoltaics (also known as agrophotovoltaics) is a new agricultural technique that combines agricultural production and solar energy in the same area (Dinesh & Pearce, 2016; Widmer *et al.*, 2024). The application of agrivoltaic systems can increase agricultural productivity and mitigate the negative effects on the environment (Gonocruz *et al.*, 2021). Thanks to its benefits, this technique has been studied and replicated in many countries in recent years. Asia is considered a continent that applies a relatively large number of agrivoltaics technique, mainly countries in Northeast Asia (Japan, South Korea, China) (Mo *et al.*, 2022); Gonocruz *et al.*, 2021; Widmer *et al.*, 2024). Japan is a leader in agrivoltaics with many projects across the country. In India, agrivoltaics is considered a potential technology for farmers and some projects have been implemented here (Mahto *et al.*, 2021).

Livestock management

Livestock management in CSA involves mainly the management of organic matter and nutrients. In Asia, livestock management practices include biogas technology, promotion of manure compositing, improvement of veterinary services, fodder crop production, improved breeds/crossbreeding (high-yielding and disease-resistant breeds), stall feeding combined with a biogas plant, improved goat shed, controlled shed, automatic feeding in controlled shed, and alternative feeds (Table 1).

Overall, in Asia, CSA technologies and practices are quite diverse and appropriate to the local contexts. While developing countries in South Asia, Southeast Asia, and Central Asia tend to primarily adopt techniques for soil and water conservation, climate change resilience, and efficient use of resources, developed countries with highly improved technology (such as Japan, Korea, and Taiwan) tend to mainly incorporate technology for emission reduction and production adaptability.

4 Factors associated with the performance and sustainability of CSA in Asia

Prioritising and selecting CSA activities require thorough consideration, not only due to the trade-off address of three criteria, or cost-benefit options of technology (Thornton *et al.*, 2018; Hussain *et al.*, 2022) but also enabling factors associated with the performance and sustainability of CSA. More than a set of practices or technologies, CSA refers to multiple interventions across agro-climate and landscape conditions, institutional settings, and socioeconomic backgrounds of smallholders (Lipper *et al.*, 2014; Chandra & McNamara, 2018).

4.1 Agro-climate and landscape characteristics

Asian countries have been facing climate change challenges and extreme weather events that negatively influence the production and livelihood security of farmers. Widespread changes in rainfall and temperature patterns threaten agricultural production and increase farmers' vulnerability (Lipper *et al.*, 2014). Soil degradation, water shortages, and salt intrusion, combined with the frequency and intensity of droughts, heatwaves, typhoons, and floods have negatively affected land and water productivity, resulting in higher production instability (Bhatt *et al.*, 2019a; Jat *et al.*, 2020). Given the diversity of geography, typography, climate, ecological conditions, and characteristics of each country, the impacts of climate change vary by production systems and agroecological zones (Nguyen *et al.*, 2017). Selecting a particular CSA practice depends significantly on the agro-climatic and landscape characteristics of a specific region.

For instance, while adoption of saline/flood-tolerant crop varieties is the primary practice in lowland or coastal regions in the face of increasing frequency of flooding and salinity intrusion (Nguyen *et al.*, 2017; Hasan *et al.*, 2018; Akter *et al.*, 2022), soil conservation agriculture technology has been paid attention in degraded soil or upland regions (Nguyen *et al.*, 2017; Bhatt *et al.*, 2019a). Respectively, drought-resistant crop and water management practices have been common in water-scarce areas with limited annual rainfall (CIAT & World Bank, 2017a; CIAT *et al.*, 2017). As climate risks are not experienced similarly across regions, CSA orientation should be location-specific and situated into unique agro-climatic and landscape characteristics of the local context.

4.2 Institutional settings

4.2.1 National and local policies and strategies

CSA has been reflected in several national and local policies and strategies of Asian countries. CSA actions are context-specific depending on regional, national and local priorities. Piloted and scaled-up CSA programs were initiated from regional levels (e.g., ASEAN Promoting CSA Practices, ASEAN Climate Resilience, SEARCA Climate Change Adaptation and Mitigation Program for Agriculture and Natural Resource Management, etc.) to national levels (such as National Action Plan on Climate Change, National Innovations on Climate Resilient Agriculture in India, Agriculture Development Strategy in Nepal, Climate Change Strategy Action Plan in Bangladesh, National Climate Change Strategy in Vietnam, Climate-Smart Agriculture Strategy in Myanmar, Climate Change Priorities Action Plan for Agriculture, Forestry and Fisheries in Cambodia, etc.) (Dinesh *et al.*, 2017; Akter *et al.*, 2022). These programs acted as guidelines, frameworks, platforms, and resources to develop CSA that aim to enhance agricultural productivity, improve sustainable resource management, and increase climate change adaptation and resilience in Asia. Based on the country's needs, these programs formulate overall directions, provide foundations, allocate resources and drive specific action plans to enable policy implementation. The involvement of non-governmental, international and domestic mass organisations, and private sectors also play an important role in providing advisory and subsidy resources to facilitate CSA.

The key feature of this process is the linkages of farming system components with governmental and non-governmental schemes to pool essential resources and help smallholders accessible with CSA practices. CSA is recognised as an efficient, sustainable, and feasible agricultural system in addressing beneficial impacts, including increased productivity, improved efficiency of resource use, and enhanced environmental durability by enhancing climate resilience and lowering GHGs (Kakraliya *et al.*, 2021; Sardar *et al.*, 2021; Imran *et al.*, 2022). Notably, during enabling policy and diffusing technology, Climate-Smart Villages (CSVs) - portfolios of CSA based on collaboration with local communities and organisations - have gained attention (Barbon *et al.*, 2021). Promoted by national programs and strategies (e.g., Vietnam's Nong Thon Moi national rural development program, Myanmar's Climate-Smart Agriculture Strategy, Philippine Department of Agriculture systemwide program, etc.) or driven by donor-funded projects (such as IDRC in Myanmar, WFP in Laos, ADB in Cambodia, etc.), CSVs aims to integrate CSA into village development plans using indigenous expertise and local needs. CSVs are sites where researchers from national and international organisations, farmers' cooperatives, local government, private sector organisations, and policymakers all come together to identify appropriate CSA interventions suited to local environmental challenges in particular villages. Since CSVs have succeeded in some Asian countries, they have provided evidence in bringing tailor-made CSA interventions to the communities through a participatory basis. However, pilot projects do not necessarily or entirely reflect the reality at scale in Asian countries, since CSV only serves as a community-specific testing ground of CSA. Broadening CSA at a larger scale still depends on other enabling factors.

4.2.2 Knowledge transfer process

CSA is perceived as not only location-specific but also technically rigorous and knowledge-intensive (Chandra *et al.*, 2017). The scaling-up of CSA can go through a knowledge transfer process via different forms, such as formal training workshops, informal farmer-farmer experience exchange, or supporting ICT tools. A comprehensive community-based training program to raise awareness of CSA can be encouraged. In the early stages of newly introduced CSA technology, formal pathways via extension workers, field researchers, and local government specialists should play an important role in providing training workshops and services to farmers on a timely basis (Pan, 2014). Learning groups (such as Farmers' Field Schools, Farmer Learning Sessions, etc.) can be appropriate platforms for designing need-based strategies and help farmers gain confidence to share their knowledge and build cooperation among peer farmers in the communities (Chandra *et al.*, 2017). Subsequently, knowledge diffusion can be promoted through informal pathways via farmer-to-farmer experience and advice sharing to disseminate CSA practices.

Some CSA could not be extended due to a lack of knowledge transfer, shortage of complete package technical training, and limited skills for operation (Aryal *et al.*, 2018;

Tran *et al*., 2020). In addition, due to the weak coordination between training providers and farmers, as well as limited guidance in action plans at local levels, farmers find it difficult to access tailored information and scale up CSA (Nguyen *et al*., 2017). As a result, the provision of adequate and transparent information, and evidence-based field research/experiment results contribute positively to advancing CSA among Asian countries at local levels (Chandra *et al*., 2017; Aryal *et al*., 2018; Tran *et al*., 2020).

4.2.3 Market condition and financial mechanism

The feasibility and sustainability of CSA should consider market conditions and financial mechanisms. High costs of installation, limited market access, and credit constraints are found to be key barriers to broadening CSA measures (Nguyen *et al*., 2017; Luu, 2020). While most CSA in Asia has been majorly led by governments or international organisations, the involvement of private sectors remains limited. Private sector engagement should be incentivised, probably in establishing market-oriented business models, providing economic incentives, or supplying investment opportunities to capture the long-term profitability and efficiency of CSA.

In addition, the success of CSA partially depends on the sustainability of financing. Although several major commitments have been made by international financial institutions, development agencies, private sectors, and national governments, many CSA activities have been funded for only short periods, and many programs just performed as pilots without the possibility to scale up. Limited financial capital for CSA investments remains a constraint for many farmers (CIAT & World Bank, 2017a; CIAT & World Bank, 2017c; CIAT *et al*., 2017). Therefore, a long-term perspective and strategy are necessary to allow farmers to perceive fully CSA concepts, as well as to realise the benefits of CSA interventions practically and sustainably. For an intervention to be successful, farming systems should be able to self-support and continue to develop solutions even after the funding has terminated. Evaluating the sustainability of a system over time without reliance on external support is critical, in which, stakeholders should engage as active participants in creating flexible operations, favourable conditions, and co-benefit interests.

4.3 Socioeconomic background of smallholders

Smallholder farming systems are common in rural villages in Asia. While considerable resources have focused on creating an enabling environment for CSA, less attention has been paid to the socioeconomic background of smallholders in facilitating and scaling out CSA while responses of smallholders to CSA practices vary with their socioeconomic diversity (Jat *et al*., 2020). Because of multi-dimensional levels of information access, household resources and subsidies, the perception of climate vulnerability and responses to CSA are diverse among smallholders. It has been found that perceived information on climate change, educational level, farmland size, farmland tenure, access to credit, extension and markets, and other social-cultural factors are critical determinants of adopting CSA practices (CIAT & World Bank, 2017a; CIAT & World Bank, 2017c; Aryal *et al*., 2018; Luu, 2020; CIAT *et al*., 2017). Some CSA practices cannot be scaled up in disadvantageous and vulnerable households due to their low affordability to access required inputs and limited operation skills (Hasan *et al*., 2018). Lack of capital, information, technical support, fragmented land plots, and limited land tenure, combined with the conventional habit of overusing agrochemicals, further create critical challenges for CSA adoption in the long term among Asian smallholders (Nguyen *et al*, 2017). As a result, CSA programs should support disadvantaged households by providing necessary resources and fostering their operation capacity. In addition, enhancing women's role in CSA also contributes to providing equitable opportunities for farmers in Asia (CIAT & World Bank, 2017a; CIAT & World Bank, 2017c; CIAT *et al*., 2017).

In sum, while growing strategies, policies, partnerships and investments create an enabling environment for CSA, it is essential to be complemented with sustainable financing, proper coordination and transparent evaluation to measure the efficacy of interventions. In recent years, based on various CSA schemes at the regional and national level, experts have used different methodologies and criteria to evaluate the effectiveness of CSA, such as smartness score (Sova *et al*., 2018), climate-smart feasibility index (Pal and Kumar, 2019), and multi-criteria ranking system (Wassmann *et al*., 2019). Despite multi-dimensional evaluation, farmers generally expressed their preference to adopt CSA conditional on improved productivity, qualified capacity, institutional favour, and market and financial approval. Strengthening household capacity, as well as facilitating the active engagement of stakeholders, are crucial to increasing CSA uptake (Bhatt *et al*., 2019b).

5 Achievements, challenges and prospects of CSA in Asia

5.1 Achievements

Our study evaluates the achievements of CSA technologies and practices based on three respective pillars of CSA, including agricultural productivity, GHG mitigation, and climate change adaptation (Table 2). The review of empirical

Table 2: *Achievements of climate smart agriculture (CSA) in Asia.*

Major groups of CSA technologies and practices	*Productivity*	*Mitigation*	*Adaptation*	*References*
Conservation agriculture	- Increased productivity/ yield/ profit - Increased farm income - Decreased poverty	Reduced GHG emissions	Increased soil moisture conservation	Sardar *et al.* (2021), Pratibha *et al.* (2015), Ghosh *et al.* (2015), Uddin *et al.* (2016), Zheng *et al.* (2014), Uddin & Dhar (2016).
Agriculture water management strategies	- Increased productivity/ yield/ profit - Savings inputs used (water, energy) - Increased farm income - Using input more efficiently - Enhanced food security	Reduced GHG emissions	Vegetation restoration, reduced soil erosion	Ha & Van Bac (2021), Nguyen & Hung (2022), Rejesus *et al.* (2011), Sardar *et al.* (2021), Imran *et al.* (2019), Imran *et al.* (2022), Mishra *et al.* (2021), Nguyen *et al.* (2017), Hasan *et al.* (2018).
Adoption of climate-resilient crop varieties	- Increased productivity/ yield/ profit - Increased farm income - Enhanced food security	Reduced GHG emissions	Climate risk adaptation	Dung & Anh (2022), Sardar *et al.* (2021), Ha & Van Bac (2021), Lan *et al.* (2018), Hasan *et al.* (2018), Nayak *et al.* (2022), Zhang *et al.* (2019).
Climate-resilient agricultural diversification	- Increased productivity/ yield/ profit - Increased farm income - Reduced poverty		Enhanced resilience to climatic shocks	Lan *et al.* (2018), Jena *et al.* (2023), Birthal & Hazrana (2019), Birthal *et al.* (2015)
Integrated pest management (IPM)	- Reduced costs of pesticide - Improved efficiency - Increased productivity/ yield	Reduced global warming		Rahman *et al.* (2018), Mariyono (2008), Mancini (2006).
Nutrient management	- Increased productivity/ yield/ profit - Increased farm income - Ensured food security	- Reduced N2O emissions and global warming - Mitigation of adverse effects of climate change	Enhanced climate resilience	Lan *et al.* (2018), Sardar *et al.* (2021), Pampolino *et al.* (2007), Singh *et al.* (2021), Islam *et al.* (2024).
Precision farming	- Increased productivity - Minimised production costs - Saved costs/cost effectiveness - Time saving	- Avoidance of overuse of agrochemicals - Reduced nitrogen	No direct contact with toxic chemicals, and enhanced public health	Chuang *et al.* (2020), UNDP (2021), Bujang & Bakar (2019), Toriyama (2020).
Agrivoltaics	- Increased productivity/ yield/ profit - Efficient land use - Reduced usage of pesticides and fertilisers - Sustainable income generation		Sustainable energy generation	Mo *et al.* (2023), Gonocruz *et al.* (2021), Mahto *et al.* (2021).
Livestock management	- Increased productivity - Utilised by-products (organic fertilisers can be used on forages) - Enhanced food security - Promotes animal health and productivity	- Reduction of negative impacts on the environment - Reduced nitrous oxide emissions	Enhanced public health and generated renewable energy	Roubík *et al.* (2017), Lopez-Ridaura *et al.* (2018)

evidence indicates that most CSA practices achieve either two or three CSA objectives.

In terms of agricultural productivity, major groups of CSA practices were proven to increase productivity or improve production efficiency, contributing to raising farm income or agricultural profit. For instance, plots adopted CA were proved to have a higher yield of 47 % than non-adopted plots in maize – wheat cropping system in India (Ghosh *et al.*, 2015). Bitter gourd production adopting IPM practices could improve higher technical efficiency compared to non-adopted production in Bangladesh (Rahman *et al.* (2018). In India, adoption of crop rotation in paddy production increased 42–45 % in farm income (Jena *et al.*, 2023). In addition to increasing productivity, CSA contributes to reducing, minimising, or saving production costs by using inputs more efficiently, particularly in agriculture water management strategies, IPM practices, PA, and agrivoltaics. In the Philippines, the application of AWD in rice production could reduce irrigation time by about 38 % and save pumping energy (Rejesus *et al.*, 2011). UNDP (2021) affirmed that smart irrigation could save 13–20 % of water used compared to the AWD model in rice fields in Vietnam. In Japan, the adoption of ICT in PA can be cost-effective and time-saving (Toriyama, 2020). Agrivoltaics also has the potential to reduce the usage of pesticides and fertilisers in production in India (Mahto *et al.*, 2021). With achievements in agricultural productivity and production resource efficiency, the adoption of CSA practices in Asia can reduce or ensure food security, decrease poverty, and improve livelihoods for farmers. In particular, the adoption of CSA practices (e.g., mulching, water management practices, adoption of climate-resilient crop varieties, and organic fertiliser) enhanced household food security in terms of food expenditure per capita in Bangladesh (Hasan *et al.*, 2018). Furthermore, intensifying livestock management could have a considerable positive impact on potential food availability in India (Lopez-Ridaura *et al.*, 2018). Moreover, crop diversification could help reduce the poverty status of Indian farmers (Birthal *et al.* 2015).

In terms of GHG mitigation, the quantitative measurements of reduced GHG and increased carbon sequestration in CSA practices are indicators of achieving the mitigation criteria. In Asia, a few studies have concentrated on GHG emissions and carbon sequestration. For instance, the study by Kakraliya *et al.* (2021) showed that the rice-wheat system under CSA practices had a lower global warming potential by 33-40 % than the conventional system in India, and thus, could mitigate global warming potential by around 387 metric tons of CO2 equivalent emissions per year. Another case study in India indicated that the application of the zero-tillage technique in the rainfed pigeon pea–castor systems could decrease GHG emissions by 21-23 % (Pratibha *et al.*, 2015). In the Lower Mekong Basin (including Lao, Vietnam, Cambodia, and Thailand), Mishra *et al.* (2021) concluded that the SRI practice helped reduce GHG emissions by 14 % per hectare with irrigated rice production and by 17 % per hectare in rainfed cropping. Additionally, a meta-analysis study of the historical changes in Chinese rice varieties reported that the replacement of new rice varieties reduced GHG emissions by about 31 % (Zhang *et al.*, 2019).

In terms of adaptability and resilience to climate change, evaluation criteria consist of the level of skills, knowledge, and exposure to climate change; the diversity of livelihoods and income sources; biodiversity and soil erosion/loss; increase in the resilience of crops/animals; and increase the resilience of natural resources. The study by Ghosh *et al.* (2015) showed that the mean runoff coefficients and soil loss of plots under conservation agriculture were 45 % and 54 % respectively less than conventional agriculture plots in the maize–wheat system in India. They also found that the soil moisture conservation was up to 90 cm soil deep after harvesting maize. Nayak *et al.* (2022) conducted a study of adaptation to the risks of climate change over three years 2016-2018 in Bangladesh. Their findings indicated that an increase in the adoption rate of climate-resilient varieties significantly enhanced farmers' adaptation to climate risks. Similarly, Birthal & Hazrana (2019) affirmed that crop diversification is a crucial adaptation measure to climatic shocks since it could create benefits against climate shocks in the long run. The UNDP report (2021) noted that precision spraying by using drones to treat armyworms can help Chinese farmers prevent direct contact with toxic insecticides and enhance public health.

Generally, CSA practices help communities improve food security, mitigate GHG emissions, and adapt to climate change by applying appropriate measures. This is an advance that transforms agri-food systems towards sustainable development.

5.2 Challenges

In addition to the achievements mentioned above, adopting and scaling up CSA in Asia still faces some key challenges. We defined and classified these challenges into six groups, including enforcing mechanisms, financial support, household capacity, technology diffusion, infrastructure, and climate change (Table 3).

In terms of enforcing mechanisms, although policies and institutional environment enable favourable conditions for CSA development, there have been limitations in enforcing guidelines, weakness in coordination among partnerships, and modest governance capacity for CSA development in some nations. For instance, there was still a shortage of directions for the development of organic farming in domestic markets in India and a lack of explicit programs targeted for CSA in Bhutan (CIAT & World Bank, 2017b). The vision and activities of some agencies related to CSA were found to overlap in the Philippines (Dikitanan *et al.*, 2017). In Nepal, fragmented institutional operations, associated with limited governance capacity and resources restricted CSA development (CIAT *et al.*, 2017). On the other hand, unfavourable land-tenure systems made farmers unwilling to invest in CSA for the long term in Bangladesh and Nepal (CIAT & World Bank, 2017a). In addition, CSA faced difficulties in replicating since farmers had limited market ac-

Table 3: *Challenges for climate smart agriculture (CSA) in Asia.*

Key challenges		*Countries*	*References*
Enforcing mechanisms	- Limited enforcing guidelines - Weak coordination among partnerships - Modest governance capacity - Unsecured land tenure - Restricted market access	Bangladesh, India, Indonesia, Kyrgyz Republic, Nepal, Pakistan, Philippines, Sri Lanka, Taiwan Thailand, Vietnam	Bhujel & Joshi (2023); Burchfield & Poterie (2018); Dikitanan *et al.* (2017); CIAT & World Bank (2017a, 2017c, 2018); FAO-SEC (2013); CIAT *et al.* (2017); Hsieh (2005); Jena *et al.* (2023); Karki & Shrestha (2014); Khamkhunmuang *et al.* (2022); Saharawat *et al.* (2022); Savelli *et al.* (2021); Thang *et al.* (2017).
Financial support	- Constrained public subsidy - Low involvement of private funding	Bhutan, Nepal, Kyrgyz Republic	CIAT & World Bank (2017b, 2018); Karki & Shrestha (2014).
Household capacity	- Limited farmer's awareness/perception - Inappropriate conventional production habits - Low capital and family labour endowment	Bangladesh, Bhutan, Cambodia, China, India, Indonesia, Kyrgyz Republic, Laos, Nepal, Pakistan, Philippines, Sri Lanka, Thailand, Vietnam	World Bank & CIAT (2015); Burchfield & Poterie (2018); Chun *et al.* (2016); Dikitanan *et al.* (2017); CIAT & World Bank (2017b, 2018); FAO-SEC (2013); Jena *et al.* (2023); Karki & Shrestha (2014); CIAT *et al.* (2017); Khamkhunmuang *et al.* (2022); Raza *et al.* (2019); Saharawat *et al.* (2022); Savelli *et al.* (2021); Thang *et al.* (2017).
Technology diffusion	- High cost of installation/investment - Lack of learning platforms	Bangladesh, Bhutan, India, Kyrgyz Republic, Nepal, Pakistan, Philippines, Sri Lanka, Vietnam	World Bank & CIAT (2015); Dikitanan *et al.* (2017); CIAT & World Bank (2017a, 2017b, 2017c, 2018); CIAT *et al.* (2017).
Infrastructure	Poor infrastructure development in transportation systems. irrigation systems	Kyrgyz Republic, Nepal, Pakistan, Sri Lanka, Vietnam	Burchfield & Poterie (2018); CIAT & World Bank (2017c, 2018); Thang *et al.* (2017); CIAT *et al.* (2017).
Climate change	Unpredictable climate change patterns	Bangladesh, Bhutan, China, India, Indonesia, Kyrgyz Republic, Nepal, Pakistan, Sri Lanka, Vietnam	World Bank & CIAT (2015); Cairns & Prasanna (2018); CIAT & World Bank (2017a, 2017b, 2017c, 2018); Jena *et al.* (2023); Saharawat *et al.* (2022); Savelli *et al.* (2021); Zhao *et al.* (2023); CIAT *et al.* (2017).

cess in Bhutan (CIAT & World Bank, 2017b) or insufficient market information in Indonesia (Savelli *et al.*, 2021). In terms of financial support, constrained public subsidy and low involvement of private funding also challenge farmers in scaling up CSA practices. Due to a lack of state funding, there were 40 % of projects not started, and 35 % of stages uncertain in implementing agricultural projects under the national sustainable development strategy of Kyrgyz Republic (CIAT & World Bank, 2018). Meanwhile, poor credit services, high interest charges or short payment periods constrained farmers from applying for CSA in Bhutan Nepal, and the Kyrgyz Republic (CIAT & World Bank, 2017b; Karki & Shrestha, 2014; CIAT & World Bank, 2018). More than 70 % of farmers in Pakistan could not access the credit (CIAT & World Bank, 2017c). As a result, increasing government funding and encouraging private-sector investment in farm equipment and machinery are recommended to advance CSA, especially CA and PA techniques (Saharawat *et al.*, 2022). In terms of household capacity, limited farmers' awareness/perception, inappropriate conventional production habits, limited capital, and low family labour endowment are key limitations that restrict farmers from adopting and scaling up CSA. For instance, while Pakistan farmers lacked technical expertise, practical skills and awareness regarding the detection and control of sugarcane pests (Raza *et al.*, 2019), Indonesian farmers have a limited understanding of the concepts of land management (Jena *et al.*, 2023). Changing farmers' tillage mindset is one of the strategic solutions for the widespread adoption of CA in Kazakhstan (FAO-SEC, 2013). In addition, the small and fragmented land hinders farmers from investing considerably in CSA in Asia. Savelli *et al.* (2021) illustrated that 75 % of households did not have a land area exceeding 1 hectare in Indonesia. In addition, inappropriate habits of conventional production methods, such as rice monoculture and excessive use of agrochemicals deterred farmers from adopting advanced CSA techniques in Bangladesh (CIAT & World Bank, 2017a). Meanwhile, poverty status and low labour endowment further obstructed farmers with CSA in Nepal and Bhutan (CIAT *et al.*, 2017; Karki & Shrestha, 2014; CIAT & World Bank, 2017b).

In terms of technology diffusion of CSA, the high cost of installation/investment, technical difficulty, and shortage of learning platforms are critical obstacles. For instance, farmers could not afford to pay for the investment expenses of CSA in the Philippines (Dikitanan *et al.*, 2017). Farmers had difficulties accessing credible agricultural data and technical knowledge since learning platforms in some areas were insufficient or outdated.

In terms of infrastructure, poor equipment in irrigation and transportation systems in some areas made CSA inapplicable. For instance, in Sri Lanka, farmers had to collectively share the irrigating water through a "pole" moved from canals to farmers' fields, therefore, they had to plant crops with the same irrigation schedule that prevented them from diversifying crops (Burchfield & Poterie, 2018). Moreover, transportation systems are inadequate to meet the current needs of the agricultural sector's requirements (CIAT & World Bank, 2017c, 2018), such as transporting heavy machines/equipment like tractors, trucks, and water pumps (Karki & Shrestha, 2014; Savelli *et al.*, 2021). Poor coverage of road connectivity to remote villages and poor quality of roads to the market limited farmers' access to CSA in Bhutan and the Philippines respectively (CIAT & World Bank, 2017b).

In terms of climate change, since climate patterns can change unpredictably and rapidly with potentially higher risks in the future (Savelli *et al.*, 2021), current CSA approaches can be inadequate to adapt to corresponding changes (Jena *et al.*, 2023). With a supporting system, farmers need to be proactive in exploring updated CSA solutions for climate resilience and adaptation.

5.3 Prospects

Despite those challenges, CSA is expected to have promising prospects since CSA-related policies and strategies play important components in the agricultural development of Asian countries. Several nations appreciate CSA thanks to evidence-based beneficial impacts of CSA for their local communities. For instance, the Philippines and Pakistan consider CSA a key priority in the development pathway (Dikitanan *et al.*, 2017; Hasan *et al.*, 2018). While Pakistan promotes CSA as a response to overcome energy shortage, Bhutan appreciates CSA in the effort of low-carbon development (CIAT & World Bank, 2017b). Many Asian countries have specified CSA in feasible action plans. In addition, the increase in public awareness of food safety, environmental conservation, and health protection provides potential opportunities for the premium and competition of the agricultural products produced by CSA measures (Bhujel & Joshi, 2023; Hsieh, 2005; Yussefi-Menzler *et al.*, 2010). As a result, beyond measurable achievements as described earlier, CSA further contributes to providing significant values of sustainable development in improving household economy, social equity and environmental quality.

6 Conclusions and policy implications

Our paper contributes to the existing literature by providing a comprehensive review and systematic evaluation of CSA in Asia, where climate change and GHG emissions have been great concerns in agricultural development. We classified adopted CSA technologies and practices in Asian countries into nine groups: conservation agriculture, water management, climate-resilient varieties, agricultural diversification, integrated pest management, nutrient management, precision farming, agrivoltaics, and livestock management. Our study fills the gap in the literature by adding newly advanced applications (e.g., precision agriculture and agrivoltaics) into CSA. Factors associated with the performance and sustainability of CSA are summarised through the linkages of enabling policies, knowledge transfer, market conditions, financial mechanisms, and the socio-economic background of smallholders. The synthesis of achievements suggests that CSA is a suitable approach for Asian farmers not only to increase productivity, but also to address food security, mitigate climate change, and enhance adaptation to climate change. In addition, key challenges include the lack of enabling guidelines, the shortage of learning platforms, limited financial support, and weak coordination between partnerships in the long term.

Based on the CSA performance in Asia, our study provides some policy implications to develop CSA in Asia in the future. First, enabling policies and strategies should be locationally specific so that related stakeholders can have clear directions and detailed guidelines for enforcing the action programs of CSA. Related partnerships (including national and international organisations, farmers' cooperatives, local government, private sector organisations, and key policymakers, etc) need to create sustainable networks, strengthen proper operations, and maintain flexible coordination to support farmers in different aspects of CSA implementation, from production investment, technology diffusion, household adoption to market access. Second, broadening the widespread learning platforms is an essential condition to help farmers conveniently access the educational resources of CSA and improve their knowledge and skills of CSA. In addition to formal training workshops via extension workers, field researchers, and local government specialists, informal peer farmer learning groups or supporting ICT tools can be useful channels to disseminate CSA practices. Rather than enhancing awareness of CSA of farmers, it is necessary to enhance the perception of consumers in the environmental and health benefits of using CSA-related products, to increase public approval for CSA. Third, ensuring financial sustainability plays a decisive role in scaling up CSA. Local governments should consider providing financial investment in public infrastructure, equipment and advanced technology supporting CSA, as well as initial subsidies and incentives for CSA farmers in disadvantaged regions. When CSA is scaled up, farming systems should be able to sustain themselves in the long term. Fourth, since climate patterns can unpredictably change in the future, the updates of advanced technology and information systems, and the engagement of multi-stakeholders at multiple levels should be promoted to enhance the capacity of farming households and help them to adopt responsive actions to local conditions. Although this study does not cover all innovative CSA practices in all agro-ecological areas in Asia, future research can consider specifically evaluating opportunities and solutions to develop these techniques.

Conflict of interest

The authors declare no conflict of interest.

Acknowledgements

This study was funded by The Vietnamese Ministry of Education and Training under research project B2024-DHH-15 of Dr. Hang Thi Thuy Nguyen.

References

Abeysekara, W. C. S. M., Siriwardana, M., & Meng, S. (2023). Economic consequences of climate change impacts on the agricultural sector of South Asia: A case study of Sri Lanka. *Economic Analysis and Policy*, 77, 435-450.

Acevedo, M., Pixley, K., Zinyengere, Meng, S., Tufan, H., Cichy, K., Bizikova, L., Isaacs, K., Ghezzi-Kopel, K., & Porciello, J. (2020). A scoping review of the adoption of climate-resilient crops by small-scale producers in low- and middle-income countries. *Nature Plants*, 6, 1231–1241.

Akter, A., Geng, X., Mwalupaso, G. E., Lu, H., Hoque, F., Ndungu, M. K., & Abbas, Q. (2022). Income and yield effects of climate-smart agriculture (CSA) adoption in flood prone areas of Bangladesh: Farm level evidence. *Climate Risk Management*, 37, 100455.

Aryal, J. P., Rahut, D. B., Maharjan, S., & Erenstein, O. (2018). Factors affecting the adoption of multiple climate-smart agricultural practices in the Indo-Gangetic Plains of India. *Nature Resources Forum*, 42(3), 141–158.

Bajwa, W. I., & Kogan, M. (2002). Compendium of IPM Definitions (CID). What is IPM and how is it defined in the Worldwide Literature? IPCC Publication No. 998, Integrated Plant Protection Center (IPPC), Oregon State University, Corvallis, OR 97331, USA.

Barbon, W. J., Punzalan, B., Wassmann, R., Bui, L. V., Vidallo, R. R., Villanueva, J., Talsma, T., Bayot, R., & Gonsalves, J. (2021). Scaling of climate-smart agriculture via climate-smart villages in Southeast Asia: insights and lessons from Vietnam, Laos, Philippines, Cambodia and Myanmar. CCAFS Working Paper.

Bhatt, R., Hossain, A., & Singh, P. (2019a). Scientific Interventions to Improve Land and Water Productivity for Climate-Smart Agriculture in South Asia. In: Hasanuzzaman, M. (eds) *Agronomic Crops*. Springer, Singapore. pp. 499–558.

Bhatt, R., Kaur, R., & Ghosh, A. (2019b). Strategies to Practice Climate-Smart Agriculture to Improve the Livelihoods Under the Rice-Wheat Cropping System in South Asia. In: Meena, R., Kumar, S., Bohra, J., Jat, M. (eds) *Sustainable Management of Soil and Environment*. Springer, Singapore. pp. 29–71.

Bhujel, R. R., & Joshi, H. G. (2023). Organic Agriculture in India: A Review of Current Status, Challenges, and Future Prospects. *Universal Journal of Agricultural Research*, 11(2), 306–313.

Birthal, P. S., Roy, D., & Negi, D. S. (2015). Assessing the impact of crop diversification on farm poverty in India. *World Development*, 72, 70–92.

Birthal, P. S., & Hazrana, J. (2019). Crop diversification and resilience of agriculture to climatic shocks: Evidence from India. *Agricultural Systems*, 173, 345–354.

Bujang, A. S., & Bakar, B. H. A. (2019). Precision agriculture in Malaysia. *Proceedings of international workshop on ICTS for precision agriculture*, pp. 6-8.

Burchfield, E. K., & de la Poterie, A. T. (2018). Determinants of crop diversification in rice-dominated Sri Lankan agricultural systems. *Journal of Rural Studies*, 61, 206–215.

Cairns, J. E., & Prasanna, B. M. (2018). Developing and deploying climate-resilient maize varieties in the developing world. *Current Opinion in Plant Biology*, 45, 226–230.

Chandra, A., Dargusch, P., McNamara, K. E., Caspe, A. M., & Dalabajan, D. (2017). A study of climate-smart farming practices and climate-resiliency field schools in Mindanao, the Philippines. *World Development*, 98, 214–230.

Chandra, A., McNamara K.E. (2018). Chapter 13 - Climate-Smart Agriculture in Southeast Asia: Lessons from Community-Based Adaptation Programs in the Philippines and Timor-Leste. *Resilience: The Science of Adaptation to Climate Change*, 165–179.

Chandra, A., McNamara, K. E., & Dargusch, P. (2018). Climate-smart agriculture: perspectives and framings. *Climate Policy*, 18(4), 526–541.

Chowdhury, D. R., & Bajracharya, S. B. (2018). Water management technologies for climate smart agriculture in South Asia: A review. *HI-AWARE work. paper*, 14, 2018.

Chuang, J. H., Wang, J. H., & Liou, Y. C. (2020). Farmers' knowledge, attitude, and adoption of smart agriculture technology in Taiwan. *International Journal of Environmental Research and Public Health*, 17(19), 7236.

Chun, J. A., Li, S., Wang, Q., Lee, W. S., Lee, E. J., Horstmann, N., *et al*. (2016). Assessing rice productivity and adaptation strategies for Southeast Asia under climate change through multi-scale crop modeling. *Agricultural Systems*, 143, 14–21.

CIAT & FAO (2018). Climate-Smart Agriculture in Punjab, Pakistan. CSA Country Profiles for Asia Series. International Center for Tropical Agriculture (CIAT); Food and Agriculture Organization of the United Nations (FAO), Rome.

CIAT & World Bank. (2017a). Climate-Smart Agriculture in Bangladesh. CSA Country Profiles for Asia Series. International Center for Tropical Agriculture (CIAT); World Bank, Washington, D.C.

CIAT & World Bank. (2017b). Climate-Smart Agriculture in Bhutan. CSA Country Profiles for Asia Series. International Center for Tropical Agriculture (CIAT); World Bank, Washington, D.C.

CIAT & World Bank. (2017c). Climate-Smart Agriculture in Pakistan. CSA Country Profiles for Asia Series. International Center for Tropical Agriculture (CIAT); World Bank, Washington, D.C.

CIAT & World Bank. (2018). Climate-Smart Agriculture for the Kyrgyz Republic. CSA Country Profiles for Asia Series. International Center for Tropical Agriculture (CIAT); World Bank, Washington, D.C.

CIAT, World Bank, CCAFS, & LI-BIRD. (2017). Climate-Smart Agriculture in Nepal. CSA Country Profiles for Asia Series. International Center for Tropical Agriculture (CIAT); The World Bank; CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS); Local Initiatives for Biodiversity Research and Development (LI-BIRD), Washington, D.C.

Coll, M., & Wajnberg, E. (2017). Chapter 1: Environmental Pest Management: A Call to Shift from a Pest-Centric to a System-Centric Approach. In: Environmental Pest Management: Challenges for Agronomists, Ecologists, Economists and Policymakers, pp. 1-17.

Deguine, J. P., Aubertot, J. N., Flor, R. J., Lescourret, F., Wyckhuys, K. A., & Ratnadass, A. (2021). Integrated pest management: good intentions, hard realities. A review. *Agronomy for Sustainable Development*, 41(3), 38.

Dhankher, O. P., & Foyer, C. H. (2018). Climate resilient crops for improving global food security and safety. *Plant, Cell & Environment*, 41(5), 877–884.

Dikitanan, R., Grosjean, G., Nowak, A., & Leyte, J. (2017). *Climate-Resilient Agriculture in Philippines. CSA Country Profiles for Asia Series*. International Center for Tropical Agriculture (CIAT); Department of Agriculture - Adaptation and Mitigation Initiatives in Agriculture, Government of the Philippines. Manila, Philippines. 24 p.

Dinesh, D., Aggarwal, P. K., Khatri-Chhetri, A., Loboguerrero Rodriguez, A. M., Mungai, C., Radeny, M. A., Sebastian, L. & Zougmoré, R. (2017). The rise in Climate-Smart Agriculture strategies, policies, partnerships and investments across the globe. *Agriculture for Development,* 30, 4–9.

Dinesh, H., & Pearce, J. M. (2016). The potential of agrivoltaic systems. *Renewable and Sustainable Energy Reviews*, 54, 299–308.

Dung, N. T., & Anh, N. T. (2022). Climate-smart agriculture and sustainability: Cost-benefit analysis in cultivation of the seedless persimmon in Ha Giang. *TNU Journal of Science and Technology*, 227(03), 54–63.

FAO. (2010). Climate-smart agriculture: Policies, practices and financing for food security, adaptation and mitigation. Food and Agriculture Organization of the United Nations (FAO), Rome.

FAO. (2013). Climate-smart agriculture sourcebook. Food and Agriculture Organization of the United Nations (FAO), Rome.

FAO-SEC. (2013). Conservation Agriculture in Central Asia: Status, Policy and Institutional Support and Strategic Framework for its Promotion. FAO Sub-Regional Office for Central Asia (FAO-SEC).

Ghosh, B. N., Dogra, P., Sharma, N. K., Bhattacharyya, R., & Mishra, P. K. (2015). Conservation agriculture impact for soil conservation in maize–wheat cropping system in the Indian sub-Himalayas. *International Soil and Water Conservation Research*, 3(2), 112–118.

Gomiero, T. (2019). Soil and crop management to save food and enhance food security. *Saving Food: Production, Supply Chain, Food Waste and Food Consumption*, 33–87.

Gonocruz, R. A., Nakamura, R., Yoshino, K., Homma, M., Doi, T., Yoshida, Y., & Tani, A. (2021). Analysis of the rice yield under an Agrivoltaic system: A case study in Japan. *Environments*, 8(7), 65.

Ha, T. M., & Bac, H. V. (2021). Effects of climate-smart agriculture adoption on performance of rice farmers in Northeast Vietnam. *Asian Journal of Agriculture and Rural Development*, 11(4), 291–301.

Hasan, M. K., Desiere, S., D'Haese, M., & Kumar, L. (2018). Impact of climate-smart agriculture adoption on the food security of coastal farmers in Bangladesh. *Food Security*, 10, 1073–1088.

Hsieh, S. C. (2005). Organic farming for sustainable agriculture in Asia with special reference to Taiwan experience. Research Institute of Tropical Agriculture and International Cooperation, National Pingtung University of Science and Technology, Pingtung, Taiwan.

Hussain, S. *et al*. (2022). Climate Smart Agriculture (CSA) Technologies. In: Jatoi, W. N., Mubeen, M., Ahmad, A., Cheema, M. A., Lin, Z., & Hashmi, M. Z. (eds). *Building Climate Resilience in Agriculture*, Springer, pp. 319–338.

Imran, M. A., Ali, A., Ashfaq, M., Hassan, S., Culas, R., & Ma, C. (2019). Impact of climate smart agriculture (CSA) through sustainable irrigation management on Resource use efficiency: A sustainable production alternative for cotton. *Land Use Policy*, 88, 104113.

Imran, M. A., Ali, A., Culas, R. J., Ashfaq, M., Baig, I. A., Nasir, S., & Hashmi, A. H. (2022). Sustainability and efficiency analysis w.r.t adoption of climate-smart agriculture (CSA) in Pakistan: A group-wise comparison of adopters and conventional farmers. *Environmental Science and Pollution Research*, 29, 19337–19351.

Islam, S. M., Gaihre, Y. K., Islam, M. N., Jahan, A., Sarkar, M. A. R., Singh, U., Islam, A., Al Mahmud, A., Akter, M., & Islam, Md. R. (2024). Effects of integrated nutrient management and urea deep placement on rice yield, nitrogen use efficiency, farm profits and greenhouse gas emissions in saline soils of Bangladesh. *Science of the Total Environment*, 909, 168660.

Jat, M. L., Jat, H. S., Agarwal, T., Bijarniya, D., Kakraliya, S. K., Choudhary, K. M., Kajod, M., Kalvaniya, K. C., Gupta, N., Kumar, M., Singh, L. K., Kumar, Y., Jat, R. K., Sharma, P. C., Sidhu, H. S., Choudhary, M., Datta, A., Paresh Bhaskar, S., & López Ridaura, S. (2020). A compendium of key climate smart agriculture practices in intensive cereal based systems of South Asia. International Maize and Wheat Improvement Center, New Delhi, India.

Jena, P. R., Tanti, P. C., & Maharjan, K. L. (2023). Determinants of adoption of climate resilient practices and their impact on yield and household income. Journal of Agriculture and Food Research, 14, 100659.

Kabir, K. H., Sarker, S., Uddin, M. N., Leggette, H. R., Schneider, U. A., Darr, D., & Knierim, A. (2022). Furthering climate-smart farming with the introduction of floating agriculture in Bangladeshi wetlands: Successes and limitations of an innovation transfer. Journal of Environmental Management, 323, 116258.

Kakraliya, S. K., Jat, H. S., Sapkota, T. B., Singh, I., Kakraliya, M., Gora, M. K., *et al*. (2021). Effect of climate-smart agriculture practices on climate change adaptation, greenhouse gas mitigation and economic efficiency of rice-wheat system in India. *Agriculture*, 11(12), 1269.

Karki, T. B., & Shrestha, J. (2014). Conservation agriculture: significance, challenges and opportunities in Nepal. *Advances in Plants & Agriculture Research*, 1(5), 186-188.

Khamkhunmuang, T., Punchay, K., & Wangpakapattanawong, P. (2022). Cases of Climate-Smart Agriculture in Southeast Asian highlands: Implications for ecosystem conservation and sustainability. *Agriculture and Natural Resources*, 56(3), 473–486.

Krippendorff, K. (2018). Content analysis: An introduction to its methodology. SAGE Publications.

Lan, L., Sain, G., Czaplicki, S., Guerten, N., Shikuku, K. M., Grosjean, G., & Läderach, P. (2018). Farm-level and community aggregate economic impacts of adopting climate smart agricultural practices in three mega environments. *Plos one*, 13(11), e0207700.

Legoupil, J. C., Lienhard, P., & Khamhoung, A. (2015). Conservation agriculture in Southeast Asia. In: Farooq, M., Siddique, K. (eds). *Conservation Agriculture*, Springer, pp. 285–310.

Lipper, L., Thornton, P., Campbell, B. M., Baedeker, T., Braimoh, A., Bwalya, M., *et al*. (2014). Climate-smart agriculture for food security. *Nature Climate Change*, 4(12), 1068–1072.

Lopez-Ridaura, S., Frelat, R., van Wijk, M. T., Valbuena, D., Krupnik, T. J., & Jat, M. L. (2018). Climate smart agriculture, farm household typologies and food security: An ex-ante assessment from Eastern India. *Agricultural Systems*, 159, 57–68.

Luu, T. D. (2020). Factors influencing farmers' adoption of climate-smart agriculture in rice production in Vietnam's Mekong Delta. *Asian Journal of Agriculture and Development*, 17(1), 110–124.

Mahto, R., Sharma, D., John, R., & Putcha, C. (2021). Agrivoltaics: A climate-smart agriculture approach for Indian farmers. *Land*, 10(11), 1277.

Mancini, F. (2006). *Impact of IPM Farmer Field Schools on the environment, health and livelihoods of cotton growers in Southern India*. Doctoral thesis, Biological Farming Systems Group, Wageningen University, The Netherlands.

Mariyono, J. (2008). Direct and indirect impacts of integrated pest management on pesticide use: a case of rice agriculture in Java, Indonesia. *Pest Management Science: formerly Pesticide Science*, 64(10), 1069–1073.

Mishra, A., Ketelaar, J. W., Uphoff, N., & Whitten, M. (2021). Food security and climate-smart agriculture in the lower Mekong basin of Southeast Asia: Evaluating impacts of system of rice intensification with special reference to rainfed agriculture. *International Journal of Agricultural Sustainability*, 19(2), 152–174.

Mo, T., Lee, H., Oh, S., Lee, H., & Kim, B. H. (2022). Economic Efficiency of Climate Smart Agriculture Technology: Case of Agrophotovoltaics. *Land*, 12(1), 90.

Nayak, S., Habib, M. A., Das, K., Islam, S., Hossain, S. M., Karmakar, B., *et al*. (2022). Adoption trend of climate-resilient rice varieties in Bangladesh. *Sustainability*, 14(9), 5156.

Nguyen, H. T. T., & Hung, P. X. (2022). Determinants of System of Rice Intensification Adoption and its Impacts on Rice Yield in the Upland Region of Central Vietnam. *Asian Journal of Agriculture and Rural Development*, 12(4), 306–315.

Nguyen, T. N., Roehrig, F., Grosjean, G., Tran, D. N., & Vu, T. M. (2017). Climate smart agriculture in Vietnam. CSA Country Profiles for Asia Series. International Center for Tropical Agriculture (CIAT); Food and Agriculture Organization of the United Nations (FAO), Hanoi, Vietnam.

Pal, B.D., Kumar, P. (2019). Prioritizing Climate-Smart Technologies in Agriculture – A Case Study in Madhya Pradesh, India. In: Pal, B., Kishore, A., Joshi, P., Tyagi, N. (eds). *Climate Smart Agriculture in South Asia*. Springer, Singapore, pp. 73–89.

Pampolino, M. F., Manguiat, I. J., Ramanathan, S., Gines, H. C., Tan, P. S., Chi, T. T. N., Rajendran, R. & Buresh, R. J. (2007). Environmental impact and economic benefits of site-specific nutrient management (SSNM) in irrigated rice systems. *Agricultural Systems*, 93(1-3), 1–24.

Pan, D. (2014). The impact of agricultural extension on farmer nutrient management behavior in chinese rice production: A household-level analysis. *Sustainability*, 6(10), 6644–6665.

Partap, T. (2010). Emerging organic farming sector in Asia: a synthesis of challenges and opportunities. Organic Agriculture and Agribusiness: Innovation and Fundamentals. Asian Productivity Organization, Tokyo, Japan.

Patton, M. Q. (2002). Qualitative research & evaluation methods. SAGE publications.

Pratibha, G., Srinivas, I., Rao, K. A., Raju, B. M. K., Thyagaraj, C. R., Korwar, G. R., Venkateswarlu, B., Shanker, A. K., Choudhary, D. K., Rao, K. S., & Srinivasarao, Ch. (2015). Impact of conservation agriculture practices on energy use efficiency and global warming potential in rainfed pigeonpea–castor systems. *European Journal of Agronomy*, 66, 30–40.

Pye-Smith, C. (2011). Farming's climate-smart future: placing agriculture at the heart of climate-change policy. CTA Policy Pointer.

Rahman, M. S., Norton, G. W., & Rashid, M. H. A. (2018). Economic impacts of integrated pest management on vegetables production in Bangladesh. *Crop Protection*, 113, 6–14.

Raihan, A., Ridwan, M., & Rahman, M. S. (2024). An exploration of the latest developments, obstacles, and potential future pathways for climate-smart agriculture. *Climate Smart Agriculture*, 100020.

Raza, H. A., Amir, R. M., Idrees, M. A., Yasin, M., Yar, G., Farah, N., & Younus, M. (2019). Residual impact of pesticides on environment and health of sugarcane farmers in Punjab with special reference to integrated pest management. *Journal Global Innovation Agriculture Social Science*, 7(2), 79–84.

Rejesus, R. M., Palis, F. G., Rodriguez, D. G. P., Lampayan, R. M., & Bouman, B. A. (2011). Impact of the alternate wetting and drying (AWD) water-saving irrigation technique: Evidence from rice producers in the Philippines. *Food Policy*, 36(2), 280–288.

Roubík, H., Mazancová, J., Phung, L. D., & Dung, D. V. (2017). Quantification of biogas potential from livestock waste in Vietnam. Agronomy Research, 15(2), 540–552.

Saab, A. (2016). Climate-resilient crops and international climate change adaptation law. *Leiden Journal of International Law*, 29(2), 503–528.

Saharawat, Y.S., Gill, M., Gathala, M.K., Karki, T.B., Wijeratne, D.B.T. & Samiullah, S. (2022). Conservation Agriculture in South Asia. In: Kassam, Amir (ed.), *Advances in Conservation Agriculture*, 3, 1–41.

Sardar, A., Kiani, A. K., & Kuslu, Y. (2021). Does adoption of climate-smart agriculture (CSA) practices improve farmers' crop income? Assessing the determinants and its impacts in Punjab province, Pakistan. *Environment, Development and Sustainability*, 23, 10119–10140.

Savelli, A., Atieno, M., Giles, J., Santos J., Leyte, J., Nguyen, N.V.B., Kostanto, H., Sulaeman, Y., Douxchamps, S., Grosjean, G. (2021). Climate Smart Agriculture in Indonesia. CSA Country Profiles for Asia Series. The Alliance of Bioversity and CIAT; The World Bank Group. Hanoi, Vietnam.

Singh, P., Benbi, D. K., & Verma, G. (2021). Nutrient management impacts on nutrient use efficiency and energy, carbon, and net ecosystem economic budget of a rice–wheat cropping system in Northwestern India. *Journal of Soil Science and Plant Nutrition*, 21(1), 559–577.

Sova, C. A., Grosjean, G., Baedeker, T., Nguyen, T. N., Wallner, M., Jarvis, A., Nowak, A., Corner-Dolloff, C., Girvetz, E., Laderach, P., & Lizarazo. M. (2018). Bringing the Concept of Climate-Smart Agriculture to Life: Insights from CSA Country Profiles Across Africa, Asia, and Latin America. World Bank, and the International Centre for Tropical Agriculture, Washington, DC.

Stenberg, J. A. (2017). A Conceptual Framework for Integrated Pest Management. *Trends in Plant Science*, 22(9), 759–769.

Strauss, A. L. (1987). Qualitative Analysis for Social Scientists. Cambridge University Press.

Tawfik, G. M., Dila, K. A. S., Mohamed, M. Y. F., Tam, D. N. H., Kien, N. D., Ahmed, A. M., & Huy, N. T. (2019). A step by step guide for conducting a systematic review and meta-analysis with simulation data. *Tropical Medicine and Health*, 47, 1-9.

Thang, T. C., Khoi, D. K., Thiep, D. H., Tinh, T. V., & Pede, V. O. (2017). Assessing the potential of climate smart agriculture in large rice field models in Vietnam. CCAFS Working Paper.

Thornton, P. K., Whitbread, A., Baedeker, T., Cairns, J., Claessens, L., Baethgen, W., *et al*. (2018). A framework for priority-setting in climate smart agriculture research. *Agricultural Systems*, 167, 161-175.

Toriyama, K. (2020). Development of precision agriculture and ICT application thereof to manage spatial variability of crop growth. *Soil science and plant nutrition*, 66(6), 811–819.

Tran, N. L. D., Rañola Jr, R. F., Ole Sander, B., Reiner, W., Nguyen, D. T., & Nong, N. K. N. (2020). Determinants of adoption of climate-smart agriculture technologies in rice production in Vietnam. *International Journal of Climate Change Strategies and Management*, 12(2), 238–256.

Uddin, M.M., & Dhar, A. (2016). Conservation agriculture practice and its impact on farmer's livelihood status in Bangladesh. *SAARC Journal of Agriculture*, 14, 119–140.

Uddin, M. T., Dhar, A. R., & Islam, M. M. (2016). Adoption of conservation agriculture practice in Bangladesh: Impact on crop profitability and productivity. *Journal of the Bangladesh Agricultural University*, 14(1), 101-112.

UNDP (2021). Precision Agriculture for Smallholder Farmers report.

Vassar, M., Atakpo, P., & Kash, M. J. (2016). Manual search approaches used by systematic reviewers in dermatology. *Journal of the Medical Library Association: JMLA*, 104(4), 302.

Vernooy, R. (2022). Does crop diversification lead to climate-related resilience? Improving the theory through insights on practice. Agroecology and Sustainable Food Systems, 46(6), 877-901.

Wassmann, R., Villanueva, J., Khounthavong, M., Okumu, B. O., Vo, T. B. T., & Sander, B. O. (2019). Adaptation, mitigation and food security: Multi-criteria ranking system for climate-smart agriculture technologies illustrated for rainfed rice in Laos. *Global Food Security*, 23, 33-40.

Weber, R. P. (1990). Basic content analysis, 49. SAGE publications.

WFO, IFA, & GACSA (2017). Nutrient Management Book.

Widmer, J., Christ, B., Grenz, J., & Norgrove, L. (2024). Agrivoltaics, a promising new tool for electricity and food production: A systematic review. Renewable and Sustainable Energy Reviews, 192, 114277.

World Bank, & CIAT. (2015). Climate-Smart Agriculture in Sri Lanka (CSA country profiles for Africa, Asia, and Latin America and the Caribbean series. The World Bank Group, Washington D.C.

Yussefi-Menzler, M., Willer, H., & Sorensen, N. (2010). The World of Organic Agriculture: Statistics and Emerging Trends 2008. International Federation of Organic Agriculture Movements (IFOAM) Bonn, Germany and Research Institute of Organic Agriculture (FiBL).

Zhang, Y., Jiang, Y., Tai, A. P., Feng, J., Li, Z., Zhu, X., Chen, J., Zhang, J. Song, Z., Deng, A., Lal, R., & Zhang, W. (2019). Contribution of rice variety renewal and agronomic innovations to yield improvement and greenhouse gas mitigation in China. *Environmental Research Letters*, 14(11), 114020.

Zhao, J., Liu, D., & Huang, R. (2023). A review of climate-smart agriculture: Recent advancements, challenges, and future directions. *Sustainability*, 15(4), 3404.

Zheng, C., Jiang, Y., Chen, C., Sun, Y., Feng, J., Deng, A., Song, Z., & Zang, W. (2014). The impacts of conservation agriculture on crop yield in China depend on specific practices, crops and cropping regions. *The Crop Journal*, 2(5), 289–296.