Revitalising agriculture through climate change mitigation: a systematic literature review on smart technologies and sustainable practices

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Abstract

Purpose – Agriculture is increasingly vulnerable to climate variability, raising critical questions about its long-term sustainability. Compounding this challenge, the agricultural sector significantly contributes to environmental degradation. As the urgency to mitigate these impacts intensifies, it becomes clear that integrated approaches to sustainable agriculture, particularly climate-smart agriculture (CSA), are essential. This study aims to explore how CSA technologies and practices can revitalise the agricultural sector to mitigate climate change while enhancing productivity resilience effectively.

Design/methodology/approach – The Preferred Reporting Items for Systematic Reviews and Meta-Analyses methodology was used to systematically screen, review and synthesise the literature on CSA technologies and practices that promote sustainable and environmentally friendly approaches.

Findings – This study categorises various technologies and practices identified in the literature into five key areas: climate-smart farming, climate-smart irrigation, climate-smart conservation, climate-smart nutrition management and integrated CSA. Transforming agriculture to address climate change requires interconnected approaches that promote sustainability across economic, social and environmental dimensions.

Originality/value – Although CSA encompasses a variety of approaches within the agricultural sector, existing studies often focus on isolated aspects. This fragmented perspective underscores the need for a more integrated examination of advanced technologies and effective practices within CSA. This study aims to bridge these gaps to maximise the benefits of CSA for sustainable agriculture and achieve the Sustainable Development Goals.

Keywords Climate change, Sustainability, Agricultural sector, Sustainable Development Goals, Climate-smart agriculture

Paper type Research paper

1. Introduction

Agriculture is the backbone of national economies, essential for developing secondary and tertiary industries (Guo *et al.*, 2022). The World Bank (2023) reports that agriculture accounts for 4% of global gross domestic product, rising to over 25% in some least developed

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countries. The Sustainable Development Goals (SDGs) further underscore agriculture as the largest global employer, providing income for 40% of the population (The World Bank, 2024). Its contributions to livelihoods are closely linked to food security, which encompasses availability, accessibility, nutritional value and stability, key components for sustaining economies [Chen *et al.*, 2022; Conde *et al.*, 2022; Food and Agriculture Organisation (FAO), 2008; Mabitsela *et al.*, 2023; Parthasarathi *et al.*, 2019; Patle *et al.*, 2020].

However, agriculture is highly vulnerable to climate variability, raising sustainability concerns (Guo *et al.*, 2022; Malhi *et al.*, 2021; The World Bank, 2024). Climate change effects, such as rising temperatures, altered precipitation patterns and increased extreme weather events like floods and droughts, pose significant risks (Intergovernmental Panel on Climate Change, IPCC, 2022; Mall *et al.*, 2017; Thai *et al.*, 2023). These changes can lead to water scarcity, soil degradation and pest infestations, negatively impacting productivity and supply chains (Malhi *et al.*, 2021; Paul *et al.*, 2018). Evidence of these disruptions includes rising production costs, shrinking agricultural land lower crop and livestock yields, and declining revenue from compromised product quality (Mok *et al.*, 2020; Sun *et al.*, 2020; Thai *et al.*, 2023).

The agricultural sector also contributes significantly to climate change. The World Bank (2023) states that one-third of global food is lost or wasted, creating health and environmental hazards and accounting for 30% of greenhouse gas (GHG) emissions. Disposing of food waste, including organic matter, via incineration releases carbon dioxide (CO_2), a major GHG (Mok *et al.*, 2020). Furthermore, agrochemical production, transport and processing contribute approximately 21%–37% of GHG emissions (FAO) (2016). As GHG concentrations rise, global temperatures are projected to increase by 2°C by 2100, leading to significant economic losses and heightening the threat to global food security (Deng *et al.*, 2017; Gancone *et al.*, 2021; Malhi *et al.*, 2021).

1.1 Climate-smart agriculture for sustainable agriculture

Rising climate variability significantly increases production risks, complicating farmers' ability to adapt and impacting secondary and tertiary industries (Guo *et al.*, 2022; Lipper *et al.*, 2014). This urgent situation highlights the need for resilient agricultural approaches (The World Bank, 2024), as the necessity to mitigate these impacts has never been more critical (Malhi *et al.*, 2021; Thai *et al.*, 2023).

In response, the concept of CSA has emerged as a vital strategy. Mizik (2021) emphasises that CSA aims to sustainably boost agricultural productivity and income, enhance resilience to climate change and reduce GHG emissions. By leveraging ecosystem services, CSA promotes agricultural systems that improve efficiency and adaptation (Ntawuruhunga *et al.*, 2023). This transformative approach not only reshapes farming practices but also plays a crucial role in ensuring food security in the face of climate change (Lipper *et al.*, 2014).

Furthermore, Gancone *et al.* (2021) note that CSA can enhance resource efficiency and contribute to achieving net-zero emissions by 2050. Supporting this, Ariani *et al.* (2018) project that implementing CSA could lead to GHG emissions reductions of 7%–23% of global warming potential (GWP). In addition, CSA can increase productivity by 0.7–1.9 tonnes per hectare, with a favourable return on investment ratio exceeding 2, making it both environmentally sustainable and economically viable, with potential gains ranging from 42% to 129%.

Ultimately, CSA interventions are crucial for enhancing long-term productivity and resilience while advancing sustainable agriculture. Accordingly, Feenstra (2020) defines sustainable agriculture as a holistic approach that prioritises ecosystem health and safeguards food security for future generations. The High-Level Panel of Experts (HLPE) (2020) reinforces this by outlining six dimensions of food security: productivity and prosperity for food availability, equity for access, empowerment of marginalised groups, resilience to shocks, regeneration and nutritional health. The FAO (2019) further defines sustainability through economic (land productivity, profitability, resilience), environmental (soil health, water usage, biodiversity) and social (employment, food security, land tenure) dimensions, highlighting the multifaceted nature of sustainable development in agriculture.

1.2 Research gaps

The CSA concept presents a promising framework for enhancing agricultural productivity, resilience and GHG emission reduction, thus contributing to sustainability. Mizik (2021) notes that this can be achieved by integrating diverse farming practices with innovative technologies such as the internet of things (IoT), artificial intelligence (AI) and robotics. Sarfraz *et al.* (2023) emphasise that this integration can revolutionise agriculture, making it smarter and more sustainable. This merging of modern technology with traditional practices marks the onset of the Fourth Industrial Revolution (4IR), termed agri-tech (Mall *et al.*, 2017; Morkunas and Balezentis, 2022; Yang *et al.*, 2021). For instance, Ntoyanto-Tyatyantsi and Amadi-Echendu (2021) illustrate how smart agriculture enables farmers to optimise production remotely, allowing precise control over crop management, including pest control, soil monitoring and moisture regulation. These advancements not only promote greener practices and enhance local agricultural capabilities but also reduce reliance on global supply chains, thus mitigating transportation-related environmental impacts (Béné, 2020; Musa *et al.*, 2022).

Nonetheless, despite the significant potential of CSA, the active involvement of full-time farmers is crucial for its successful adoption, highlighting the necessity of their participation in effective climate initiatives (Mizik, 2021). However, the literature remains unclear on various farming systems and agronomic practices relevant to CSA (Lipper *et al.*, 2014; Mizik, 2021). While CSA encompasses diverse approaches within agriculture, existing studies often focus on isolated aspects, limiting a comprehensive understanding of its overall potential. For example, Lalrochunga *et al.* (2024) and Ntawuruhunga *et al.* (2023) delve into smart agroforestry, whereas Alomar and Alazzam (2018) and Patle *et al.* (2020) investigate smart water management. This fragmented focus underscores the need for a more integrated examination of technologies and practices within CSA to fully realise its benefits for sustainable agriculture.

In light of these challenges, Daka (2023) calls for further research to address significant gaps in the literature regarding strategies to mitigate climate change for sustainability. Similarly, Ntawuruhunga *et al.* (2023) emphasise the limited focus on CSA's impact on food security, despite acknowledging its positive outcomes, such as increased productivity and socio-economic benefits compared to monoculture practices. Lipper *et al.* (2014) further stress the importance of evaluating the adaptation and mitigation potential of various technologies and practices, considering both extreme events and gradual changes affecting agriculture and food security. Collectively, these insights highlight the critical need for comprehensive research to fully understand the multifaceted role of CSA in promoting sustainability and resilience in agriculture.

Therefore, this study aims to systematically review the literature to explore how CSA can revitalise the agricultural sector in mitigating climate change. The central research questions are: What options for smart technologies and effective practices exist within the farming sector? How do these CSA initiatives generate positive outcomes in the face of climate change? By addressing these questions, this study seeks to fill existing research gaps regarding the diversity of sustainable agriculture, encompassing technologies and practices that mitigate climate change while promoting sustainability. Ultimately, this systematic literature review (SLR) will provide valuable insights into current research and strategic directions necessary for effectively addressing pressing climate change challenges, thereby supporting future initiatives (Adenle *et al.*, 2015; Guo *et al.*, 2022; Mall *et al.*, 2017; Thai *et al.*, 2023; Yang *et al.*, 2021).

The SLR process is outlined in Section 2, followed by a comprehensive discussion of the findings in Section 3. Section 4 summarises the outcomes of this study.

2. Methodology

Scholars like El Chami *et al.* (2022) and Malhi *et al.* (2021) emphasise the importance of SLR in assessing research critical for mitigating climate change impacts in agriculture. Owen (2020) supports this, noting that a comprehensive understanding of these issues can be achieved through literature reviews.

This study used an SLR to explore CSA, focusing on technologies and practices that promote sustainable, environmentally friendly methods to mitigate climate change effects in farming. To ensure thoroughness and accuracy, the authors used the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) technique, recognised for its robust reporting standards (Page *et al.*, 2021). The PRISMA method consists of four phases for paper selection: identification, screening, eligibility and inclusion. Key steps in the PRISMA process are outlined in the following subsections.

2.1 Identification phase

At the identification stage, relevant literature was accessed and gathered from the Scopus and Emerald databases. Although ScienceDirect was initially considered, the overwhelming volume of results for the identified keywords led to a decision to focus on the two more manageable databases. Boolean operators were used to search within the title, abstract and keywords, following the guidelines of Daka (2023) and Ntawuruhunga *et al.* (2023).

In Scopus, the search string used was: (agriculture) OR (smart agriculture) AND (smart technologies) OR (4IR technologies) OR (agri-tech) AND (climate change mitigation) OR (climate change), yielding 1,078 publications.

In Emerald, a different search string was employed: (climate-smart agriculture [CSA]) AND (climate change mitigation), to minimise redundancy and enhance variety, resulting in 197 publications.

2.2 Screening phase

A total of 1,275 initially identified studies underwent a rigorous screening process to retain only those meeting the inclusion criteria, as summarised in Table 1. Firstly, publications were limited to a 10-year timeframe from 2014 to 2024, marked by a significant increase in journal volume, offering valuable insights across various research domains (Aamer *et al.*, 2021; Sheppard, 2016).

Secondly, all studies had to be in English to align with the authors' proficiency and minimise the risk of misinterpretation due to translation issues, enhancing clarity and accessibility for researchers (Daka, 2023; Mizik, 2021; Ntawuruhunga *et al.*, 2023). Thirdly, studies needed to address CSA themes, particularly smart/advanced technologies, sustainable practices and overall climate change mitigation in the agricultural sector, ensuring relevance for the analysis.

Fourthly, only peer-reviewed academic journal articles and conference proceedings were considered to maintain high quality. In addition, articles had to be open access to facilitate accessibility for authors without institutional subscriptions. There were also no restrictions

Table 1. Inclusion and exclusion criteria for literature review

	Inclusion criteria	Exclusion criteria
Publication year	Literature published between 2014 and 2024	Literature published before 2014
Publication language	Literature in the English language	Literature not in the English language
Publication focus	Literature on CSA, climate change mitigation and agriculture	Literature outside the stated scope of relevance
Publication type	Academic journal articles and conference proceedings	Book chapters, book series, editorials, trade publications and letters
Others	Fully available peer-reviewed open access articles and studies from any country	Duplicate studies

Source(s): Adopted from Ntawuruhunga *et al.* (2023)

based on the country of publication, allowing for a comprehensive examination of the phenomenon, and duplicate entries were removed.

2.3 Eligibility phase

The screened articles were then sorted by relevance to the topic. Firstly, the abstracts were reviewed, followed by a thorough reading of the full texts to ensure that only the most pertinent articles were included in the SLR. Consequently, 336 articles were excluded for not aligning with the defined scope.

2.4 Inclusion phase

Figure 1 illustrates the PRISMA flowchart for this study. A total of 53 articles were included in the final synthesis, providing a comprehensive understanding of how CSA can revitalise the agricultural sector to mitigate climate change. Other scholars have reported varying numbers of studies in their PRISMA research: Tariku and Kebede (2024) included 42 articles, Daka (2023) included 34 and Ma and Rahut (2024) included 19. This variation suggests the focus should be on whether the selected articles effectively address the research aims.

Chanza and Musakwa (2022) note that PRISMA studies offer a thorough, if not exhaustive, understanding of the topic. Although the authors recognise that PRISMA aids in the selection process, Lalrochunga *et al.* (2024) argue that it may not fully explore the

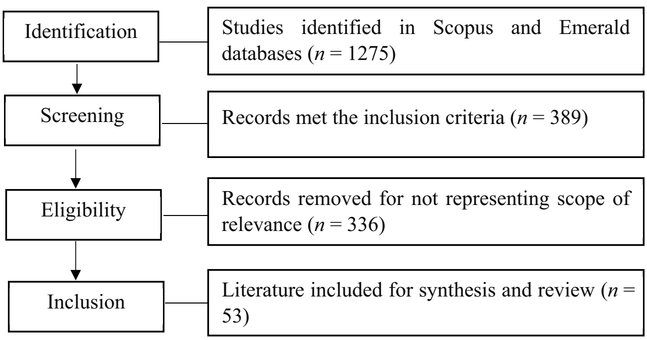

Figure 1. PRISMA flowchart
Source(s): Authors' own work

interrelations of identified themes. In addition, the manual review process may have missed some studies due to its time-consuming nature.

Despite these limitations, this review's thematic analysis successfully identifies specific CSA technologies and practices, highlighting their positive impacts on mitigating climate change and promoting sustainable agriculture. This approach underscores the rigour of the review while providing valuable insights into achieving sustainability.

3. Findings and discussions

This SLR underscores the importance of integrating advanced technologies and effective practices to bridge the supply-demand gap in agriculture (Neme *et al.*, 2021; Suhaili, 2023). This need has led to the emergence of CSA, which aims to combat environmental degradation and food insecurity (Gancone *et al.*, 2021; Mabitsela *et al.*, 2023). In connection with this, this study categorises CSA into five areas: Climate-Smart Farming, Climate-Smart Irrigation, Climate-Smart Conservation, Climate-Smart Nutrient Management and Integrated CSA. For context, only a few previous studies offer a comprehensive view of these categories, with notable exceptions including Aryal *et al.* (2018) and Sahoo *et al.* (2023). This highlights a gap that this study aims to address. Table 2 summarises the selected literature, revealing that only 22 articles employed quantitative methods, yet they still offer valuable insights into CSA's impact on agricultural sustainability. Given the predominance of qualitative studies, this study emphasises descriptive findings to explore the various dimensions of CSA and its implications for sustainable agriculture.

In essence, CSA seeks a "triple win" by addressing climate change mitigation and adaptation while ensuring food security. This holistic approach incorporates diverse technologies and practices, establishing CSA as a sustainable farming strategy that optimises resource use, enhances long-term viability, reduces environmental degradation and GHG emissions and increases agricultural income (Kichamu-Wachira *et al.*, 2021; Ma and Rahut, 2024; Mekyassi and Kızıldeniz, 2024; Paul *et al.*, 2018; Rao, 2018; Saj *et al.*, 2017).

Supporting these claims, Meshesha *et al.* (2022) found that farmers believe adopting CSA enhances food security, with 91% and 80% of respondents affirming increased productivity and income. In addition, 86% noted improvements in climate adaptation and soil fertility, while 64% recognised potential GHG emission reductions. Ariani *et al.* (2018) project that CSA implementation could reduce GHG emissions by 7%–23% and increase productivity by 0.7–1.9 tonnes per hectare. With a favourable return on investment ratio exceeding 2, CSA demonstrates both environmental sustainability and economic viability, with potential gains of 42%–129%.

Sahoo *et al.* (2023) argue that leveraging CSA will position current agricultural practices to effectively contribute to several SDGs, including SDG 2 (Zero Hunger), SDG 13 (Climate Action) and SDG 15 (Life on Land). Ntawuruhunga *et al.* (2023) further emphasise that CSA offers numerous ecological and economic benefits that support multiple SDGs, particularly SDG 1 (No Poverty), SDG 3 (Good Health and Well-Being), SDG 6 (Clean Water and Sanitation) and SDG 7 (Affordable and Clean Energy).

The following subsections explore emerging themes related to CSA and their role in mitigating the impacts of climate change in agriculture.

3.1 Climate-smart farming

This subsection explores technologies and practices that enhance agricultural productivity while promoting environmental sustainability and resilience to climate change.

3.1.1 Smart technologies. Numerous climate-smart technologies are emerging as effective strategies for sustainable farming. For instance, *crop-livestock integrated farming*

Table 2. Summary of included literature

No.	Authors and years	Country	Methodology	CSA	Technologies/ practices
1	Ma and Rahut (2024)	General	Qualitative	CSA	General
2	Meshesha *et al.* (2022)	Ethiopia	Quantitative	CSA	General
3	Gancone *et al.* (2021)	Latvia	Qualitative	CSA	General
4	Ariani *et al.* (2018)	Indonesia	Quantitative	CSA	General
5	Swarnam *et al.* (2024)	India	Quantitative	Climate-smart farming	Crop-livestock integrated farming
6	Amondo *et al.* (2019)	Africa	Quantitative	Climate-smart farming	Drought-tolerant maize varieties
7	Deng *et al.* (2017)	China	Mixed	Climate-smart farming	Cropping system innovations
8	Zedler *et al.* (2023)	UK	Quantitative	Climate-smart farming	Multiplex sensors
9	Balaska *et al.* (2023)	European Union	Qualitative	Climate-smart farming	Advanced solutions
10	Yusoff *et al.* (2023)	Malaysia	Quantitative	Climate-smart farming	Hydroponic verticulture system
11	Kumar *et al.* (2024)	General	Qualitative	Climate-smart farming	IoT
12	Symeonaki *et al.* (2019)	General	Qualitative	Climate-smart farming	IoT
13	Mabitsela *et al.* (2023)	Africa	Quantitative	Climate-smart farming	IoT aeroponics
14	Mok *et al.* (2020)	Singapore	Qualitative	Climate-smart farming	IoT aeroponics
15	Rao (2018)	India	Qualitative	Climate-smart farming	Big data
16	Creydt and Fischer (2019)	General	Qualitative	Climate-smart farming	Blockchain
17	Vărzaru (2024)	European Union	Quantitative	Climate-smart farming	Digitalisation
18	Alhassan *et al.* (2021)	China	Quantitative	Climate-smart farming	Conservation tillage
19	Kichamu-Wachira *et al.* (2021)	Africa	Qualitative	Climate-smart farming	Conservation tillage
20	Huang *et al.* (2018)	China	Qualitative	Climate-smart farming	Conservation tillage
21	Pratibha *et al.* (2019)	India	Qualitative	Climate-smart farming	Animal drawn tillage
22	Conde *et al.* (2022)	Peru	Quantitative	Climate-smart farming	Agroecology
23	Spring *et al.* (2021)	General	Qualitative	Climate-smart farming	Agroecology
24	Saj *et al.* (2017)	India	Qualitative	Climate-smart farming	Agroecology
25	Martin-Guay *et al.* (2018)	General	Qualitative	Climate-smart farming	Intensification
26	Paul *et al.* (2018)	Africa	Quantitative	Climate-smart farming	Intensification
27	Driscoll *et al.* (2024)	USA	Quantitative	Climate-smart irrigation	Quantification of irrigation-related emissions
28	Chen *et al.* (2022)	China	Quantitative	Climate-smart irrigation	Water-centric smart microclimate control system
29	Parthasarathi *et al.* (2019)	India	Quantitative	Climate-smart irrigation	Drip irrigation
30	Alomar and Alazzam (2018)	General	Qualitative	Climate-smart irrigation	Intelligent irrigation
31	Mizik (2021)	General	Qualitative	Climate-smart irrigation	Water management
32	Suhaili (2023)	Brunei Darussalam	Qualitative	Climate-smart irrigation	Safe alternate wetting and drying (AWD)
33	Mboyerwa *et al.* (2021)	Africa	Quantitative	Climate-smart irrigation	AWD

(*continued*)

Table 2. Continued

No.	Authors and years	Country	Methodology	CSA	Technologies/ practices
34	Deelstra *et al.* (2018)	India	Quantitative	Climate-smart irrigation	AWD
35	Patle *et al.* (2020)	India	Qualitative	Climate-smart irrigation	Water innovations
36	Veste *et al.* (2020)	Africa	Quantitative	Climate-smart irrigation	Windbreak hedges
37	Daka (2023)	Africa	Qualitative	Climate-smart conservation	Clean technologies
38	Molua *et al.* (2023)	Africa	Quantitative	Climate-smart conservation	Reforestation
39	Chanza and Musakwa (2022)	Africa	Qualitative	Climate-smart conservation	Indigenous food management practices
40	Ntawuruhunga *et al.* (2023)	General	Qualitative	Climate-smart conservation	Climate-smart agroforestry
41	Jahanzad *et al.* (2020)	USA	Quantitative	Climate-smart conservation	Whole orchard recycling
42	Carlsson *et al.* (2017)	Sweden	Quantitative	Climate-smart conservation	Perennial species mixtures
43	Michler *et al.* (2019)	Africa	Quantitative	Climate-smart conservation	Conservation agriculture
44	Babu *et al.* (2022)	General	Qualitative	Climate-smart nutrient management	Nanofertilisers
45	Mekyassi and Kızıldeniz (2024)	General	Qualitative	Climate-smart nutrient management	Nutrition-sensitive climate smart agriculture
46	Pham *et al.* (2023)	Vietnam	Qualitative	Integrated climate-smart agriculture	Innovative and smart agriculture platform
47	Sahoo *et al.* (2023)	General	Qualitative	Integrated climate-smart agriculture	Intercropping system technologies
48	Azadi *et al.* (2021)	General	Qualitative	Integrated climate-smart agriculture	Vulnerable-smart agriculture
49	Neme *et al.* (2021)	General	Qualitative	Integrated climate-smart agriculture	Nanotechnology
50	Lowry *et al.* (2019)	General	Qualitative	Integrated climate-smart agriculture	Nanotechnology
51	Tariku and Kebede (2024)	Ethiopia	Qualitative	Integrated climate-smart agriculture	Multiple agricultural practices
52	Aryal *et al.* (2018)	India	Quantitative	Integrated climate-smart agriculture	Multiple agricultural practices
53	Harvey *et al.* (2014)	General	Qualitative	Integrated climate-smart agriculture	Agricultural landscapes

Source(s): Authors' own work

approaches are used on humid tropical islands, such as those in India (Swarnam *et al.*, 2024). These methods incorporate technologies like rainwater harvesting and intensive vegetable cultivation, enhancing land management, fostering biodiversity and optimising resource use. This holistic approach supports local economies and food security. In addition to integrated farming, Amondo *et al.* (2019) highlight *drought-tolerant maize varieties (DTMV)*, designed to improve crop resilience in water-scarce environments. The adoption of DTMV resulted in a 15% increase in maize yields, a 38% reduction in yield variability and a 36% decrease in downside risk, underscoring its economic benefits for farmers facing climate challenges. China has also successfully adapted *cropping system innovations*, including new cultivar breeding and optimisation of cropping practices, to capitalise on the positive effects of climatic warming. These adaptations have led to increased crop yields, higher resource use efficiency and a significant rise in soil organic carbon (SOC) content, all while reducing GHG emissions (Deng *et al.*, 2017).

Addressing production challenges is unarguably essential, and early optical detection of crop stress plays a pivotal role in reducing waste. To illustrate this, Zedler *et al.* (2023) conducted research in the UK using *multiplex sensors* that can detect up to six plant volatiles through changes in colour intensities. These measurements enable early detection of abiotic stress within as little as two days after exposure to stressors, allowing timely interventions that safeguard yields and promote sustainable farming practices.

In the European Union, Balaska *et al.* (2023) found that *robotic and AI-driven solutions* significantly outperform traditional farming methods. Specifically, robots can detect pests and apply targeted treatments, reducing chemical usage and environmental harm. Meanwhile, AI algorithms analyse weather, soil and crop data to predict threats and recommend preventive measures, empowering farmers to make informed decisions. This enhanced precision not only lowers labour costs but also promotes sustainable methods that benefit both the environment and economic stability.

The integration of animal components into farming systems further boosts productivity and sustainability, contributing to reduced net GHG emissions and lower emission intensity. For example, in Malaysia, Yusoff *et al.* (2023) advocate for the *hydroponic verticulture system (HVS)*, a soil-less urban agri-tech solution that promotes urban farming, ensures food quality and encourages community engagement. By using a full tank of water or mixed organic material totalling 13.5 L, HVS effectively nourishes crops while simultaneously mitigating climate change through reduced CO_2 levels and increased O_2 levels, showcasing a balance of economic, social and environmental benefits.

IoT technologies offer transformative potential in agriculture by enabling informed decision-making and optimising resource use. According to Kumar *et al.* (2024), IoT supports precision agriculture that maximises crop yields while minimising inputs. This approach leads to cost savings through efficient resource utilisation and reduces environmental impact. Symeonaki *et al.* (2019) share a parallel view that the widespread IoT adoption in controlled agriculture is essential for boosting productivity and lowering costs, thereby enhancing sustainability and supporting global development goals.

Aquaponics represents another innovative avenue, integrating IoT to enhance agricultural efficiency and productivity. This has been demonstrated in research by Mabitsela *et al.* (2023), where the authors studied the cultivation of the underused indigenous African legume, Bambara groundnut, revealing notable advantages when grown in aeroponics compared to traditional hydroponic methods using sawdust and drip irrigation. The findings indicated improved plant height and chlorophyll content, offering cost-effective solutions for climate change adaptation and food security. Correspondingly, Mok *et al.* (2020) highlighted AeroFarms in Singapore, which uses aeroponic systems that operate on less than 1% of land and use 95% less water compared to conventional farming methods, all while adhering to stringent quality and food safety standards, ensuring both economic feasibility and environmental sustainability.

Other 4IR technologies further offer significant potential for enhancing agricultural insights. According to Rao (2018), *big data* can revolutionise agriculture by:

- developing predictive capabilities to anticipate the impacts of climate change on farming;
- accelerating plant breeding to improve productivity and resilience; and
- delivering personalised, real-time recommendations for optimising productivity while adapting to climate challenges.

In addition, Creydt and Fischer (2019) assert that *blockchain* technology ensures transparency and accountability in the food supply chain, helping detect safety issues and fraudulent activities, thereby fostering consumer trust and enhancing social sustainability. Vărzaru (2024) supports these findings, noting that digitalisation significantly boosts labour productivity in agriculture, benefiting both the environment and the economy.

3.1.2 Sustainable practices. Tillage practices are critical for sustainable farming within the framework of CSA (Alhassan *et al.*, 2021; Huang *et al.*, 2018; Kichamu-Wachira *et al.*, 2021; Pratibha *et al.*, 2019). Alhassan *et al.* (2021) demonstrate that conservation tillage has positive effects in dryland ecosystems, notably reducing net CO_2 flux and enhancing CH_4 absorption, whereas its impact on N_2O emissions is relatively minor. These benefits are largely due to significant improvements in SOC and total nitrogen, particularly in the topsoil layer (0–20 cm). For instance, no-till with straw mulch (NTC) has been shown to lower both GWP and yield-scale GWP, while improving soil water content, reducing soil temperature and increasing average grain yield. Likewise, Huang *et al.* (2018) reported a 22% reduction in CO_2 and CH_4 emissions in rice fields using sustainable tillage practices, indicating strong potential for GWP reduction.

Kichamu-Wachira *et al.* (2021) further highlight that conservation tillage can enhance SOC pools through increased carbon inputs, thus improving soil quality and boosting crop productivity. This is particularly beneficial for resource-constrained smallholder farmers, as it offers higher yields at lower costs, directly supporting their livelihoods. Pratibha *et al.* (2019) noted that tillage implements designed for minimal soil disturbance result in lower GWP and energy input. Specifically, animal-drawn tillage implements are associated with reduced emissions of CO_2, N_2O and CH_4, while also requiring less energy, showcasing a balance of environmental and economic advantages.

Agroecology further complements sustainable farming as it responds to site-specific needs and local practices, facilitating farmer adoption (Conde *et al.*, 2022; Saj *et al.*, 2017; Spring *et al.*, 2021). Saj *et al.* (2017) argue that an ecological and sociological approach to CSA is vital for promoting inclusive development and fostering collective efforts to manage agriculture and food systems in the face of climate change. This holistic perspective enhances community food systems by integrating biological, cultural and community diversity, contributing to food sovereignty and resilience while promoting synergies between productivity and climate adaptation.

Beyond tillage and agroecology, *crop intensification practices*, such as providing access to inorganic fertilisers and improved seeds, present viable solutions for increasing production without further land clearing (Paul *et al.*, 2018). Martin-Guay *et al.* (2018) conducted a comprehensive global meta-analysis of 939 sources, recommending intensification through intercropping. Specifically, the simultaneous production of multiple crops on the same land area, along with irrigation strategies, showed no significant impact on the land equivalent ratio, indicating that intercropping remains beneficial under both stressful and non-stressful moisture conditions. Furthermore, various fertilisation methods and intercropping patterns (rows and strips vs mixed) did not significantly affect the land equivalent ratio, underscoring the adaptability of these practices to diverse farming contexts.

3.2 Climate-smart irrigation

This subsection explores technologies and practices that enhance water management in agriculture, aiming to improve crop resilience and reduce waste.

3.2.1 Smart technologies. Efficient water use and management in agriculture are crucial for adapting to climate change, especially as rising temperatures and erratic precipitation patterns lead to increasing water scarcity, particularly in drought-prone and non-irrigated regions. In response, Patle *et al.* (2020) advocate for an integrated approach to *agricultural water management*. This approach encompasses innovative practices such as water harvesting, micro-irrigation and resource conservation methods like hydroponics and aquaponics, all aimed at enhancing water-use efficiency while contributing to economic stability and food security.

While rain-fed and irrigation methods are commonly used to supply water to paddy crops, the literature emphasises the effectiveness of irrigation. In particular, Parthasarathi *et al.* (2019) investigated a water-saving technique designed to enhance yield and mitigate methane emissions in aerobic rice cultivation, concluding that *drip irrigation* is a frontrunner. The Subsurface Drip Irrigation technique, with a discharge rate of 1.0 L per hour, proves especially effective in water-scarce regions. This method not only reduces CO_2-equivalent emissions but also delivers higher yields compared to conventional flood irrigation methods, thus supporting both environmental and economic sustainability.

Similarly, Alomar and Alazzam (2018) introduced an innovative irrigation system based on IoT, integrating fuzzy logic to create *intelligent irrigation* solutions. This system optimises irrigation frequency and boosts production rates while enhancing water conservation. By addressing water stress effectively, these technologies contribute to sustainable agricultural practices that benefit farmers economically.

Moreover, Driscoll *et al.* (2024) argue that reducing emissions from irrigation requires a comprehensive approach that includes not only decarbonising on-farm pumping but also *quantifying irrigation-related emissions*. This quantification is essential for identifying feedback loops that mediate adaptation and targeting efforts to reduce GHG emissions. Given the heavy reliance on electric pumps, projected reductions in electrical grid emissions intensity are estimated to decrease pumping emissions by 46% by 2050, with additional reductions possible through pump electrification. These strategies can significantly contribute to the overall sustainability of agricultural operations.

In addition, Chen *et al.* (2022) introduced a *water-centric smart microclimate-control system*, which offers a remarkable 66% reduction in water and electrical energy consumption compared to traditional greenhouse spraying methods that depend on operator experience. By integrating system dynamics and machine-learning techniques to optimise internal hydro-meteorological processes, this innovation not only enhances water efficiency but also reduces operational costs, further aligning agricultural practices with sustainability goals.

3.2.2 Sustainable practices. According to Mizik (2021), irrigation development could generate annual revenues of $14–22bn, significantly improving the livelihoods of 113–329 million rural residents. This highlights the transformative potential of CSA practices in enhancing both economic and social outcomes.

One widely advocated technique is *safe alternate wetting and drying (AWD)*, which involves irrigating fields only after ponded water has evaporated, allowing water levels to drop to about 15 cm below the soil surface before re-irrigation. AWD is crucial for sustainable rice production, significantly reducing GHG emissions (Deelstra *et al.*, 2018; Mboyerwa *et al.*, 2021; Suhaili, 2023). Deelstra *et al.* (2018) conducted extensive measurements in India, revealing that AWD not only requires less water compared to direct-seeded or conventional paddy rice but also improves water productivity, aiming for a higher "crop per drop".

Correspondingly, Mboyerwa *et al.* (2021) demonstrated in a greenhouse pot experiment that combining AWD with nitrogen application (60–80 kg/ha) significantly boosts yields. Their findings indicated an enhancement in water productivity of up to 1.5 kg per cubic metre, leading to a 34.3% water savings compared to continuous flooding. Suhaili (2023) also reported that integrating AWD with a smart watering system in Brunei could conserve up to 25% of water, showcasing the economic and environmental benefits of this technique.

Technological advancements, such as AI-driven systems, can further optimise soil and water management, facilitating smart irrigation and precise application of fertilisers and pesticides.

In addition, Veste *et al.* (2020) highlighted the role of tree shelterbelts in reducing wind speeds, presenting an eco-engineering solution for water conservation in vineyards. These *windbreak hedges* effectively reduce wind speeds, leading to lower reference evapotranspiration and improved water conservation. For example, measurements 18 m from the hedgerow showed a wind speed reduction of 27.6% annually and 39.2% during the summer. This resulted in a 15.5% decrease in reference evapotranspiration over the year and an 18.4% reduction in the growing season, highlighting their role in enhancing water efficiency and supporting sustainable agriculture.

3.3 Climate-smart conservation

This subsection explores technologies and practices that promote the sustainable use and conservation of natural resources, enhancing ecosystem health and agricultural productivity.

3.3.1 Smart technologies. According to Daka (2023), *clean technologies* use renewable fuels and resources, benefiting the environment and livelihoods. By reducing reliance on fossil fuels, they significantly lower CO_2 emissions and promote sustainability, particularly in deforestation-prone areas. Integrating renewable energy with sustainable resource management decreases pollution and firewood dependence, boosting economic productivity while minimising environmental degradation. This approach enhances social well-being by promoting cleaner air and healthier ecosystems, contributing to a more sustainable future.

3.3.2 Sustainable practices. Embracing climate-smart conservation agriculture practices is essential for sustainable agricultural systems. Molua *et al.* (2023) emphasise the importance of integrating *farm trees and reforestation*, which ensures access to vital natural resources while preserving biodiversity and ecosystem services. By further adopting a mixed approach that combines crops, livestock and trees, farmers can enhance profitability and build resilience against climate variability. This holistic strategy not only supports economic stability but also fosters environmental health and social cohesion within farming communities.

In this context, Chanza and Musakwa (2022) highlight the value of *indigenous food management practices* that improve the gathering and preservation of native fruit trees. These practices provide health benefits through a variety of sources, including edible insects, traditional herbs and leafy vegetables. In addition, Ntawuruhunga *et al.* (2023) demonstrate that *climate-smart agroforestry* enhances food security by promoting diverse species that yield food and surplus for sale. Increased biodiversity and higher yields not only improve food security but also generate significant income from fruits, vegetables and non-timber forest products, fostering both financial stability and social cohesion. Furthermore, practices like pruning integrated crop trees for fuelwood support biomass and carbon storage, contributing to a shift from deforestation to sustainable methods.

Effective waste management also plays a critical role. Jahanzad *et al.* (2020) found that biomass recycling, particularly *whole orchard recycling (WOR)* in irrigated almond orchards, significantly enhances soil function by increasing nutrient content, aggregation and water retention. This method boosts carbon sequestration by five metric tonnes per hectare compared to burning and improves irrigation water-use efficiency by 20%. In Sweden, Carlsson *et al.* (2017) advocate for cultivating unfertilised, species-rich *perennial plant mixtures* on marginal lands. These mixtures produce resource-efficient biomass while fostering synergies between productivity and biodiversity, requiring minimal inputs and aligning with sustainability goals.

Overall, conservation agriculture effectively minimises yield losses in areas facing increased weather risks, ensuring greater resilience under both high and low rainfall conditions compared to traditional practices (Michler *et al.*, 2019). This interconnected approach underscores the vital links between agricultural practices, environmental sustainability and community well-being.

3.4 Climate-smart nutrient

This subsection explores technologies and practices that optimise nutrient use in agriculture, aiming to enhance crop yields while minimising environmental impact.

3.4.1 Smart technologies. Babu *et al.* (2022) have highlighted the promising use of *nano-fertilisers (NFs)* in advancing cleaner and safer crop production, contributing significantly to environmental sustainability. As an effective alternative to traditional chemical fertilisers, NFs offer enhanced nutrient-use efficiency, boosting overall agricultural productivity. Moreover, they improve plant resilience against both biotic and abiotic stressors, underscoring their vital role in modern, sustainable agricultural practices.

3.4.2 Sustainable practices. Mekyassi and Kızıldeniz (2024) underscore the need to integrate nutrition into CSA policies. The authors propose *nutrition-sensitive climate-smart agriculture (NSCSA)*, which addresses food security, nutrition and climate change simultaneously. By promoting nutrient-rich foods, particularly for vulnerable populations like women and children, NSCSA aims to combat malnutrition while enhancing income and agricultural productivity. Sustainable practices such as agroforestry and conservation agriculture further support this approach, fostering both health and environmental resilience.

3.5 Integrated climate-smart agriculture

This subsection explores a comprehensive approach that integrates various innovative agricultural technologies and practices to enhance resilience and sustainability in farming systems.

3.5.1 Smart technologies. The transformative potential of emerging technologies presents significant benefits for sustainable agriculture by aligning economic viability, social empowerment and environmental sustainability. In Vietnam, the *innovative and smart agriculture platform* collects real-time data to generate reports and science-based recommendations, optimising productivity, promoting efficient resource use, and controlling costs, ultimately supporting sustainable agricultural practices (Pham *et al.*, 2023).

In tandem with these innovations, Sahoo *et al.* (2023) advocate for *intercropping systems* that integrate water, energy, nutrients and other climate-smart approaches. For instance, maize-pea intercropping reduces carbon emissions by 2.8 tonnes per hectare, approximately 31% less than monoculture maize. Similarly, sorghum-cowpea intercropping leads to over a 15% reduction in CO_2 emissions during critical growth periods compared to sole cropping. These systems not only mitigate environmental impacts but also enhance agricultural resilience, as evidenced by a land equivalent ratio greater than one. Conversely, Azadi *et al.* (2021) emphasise the *vulnerable-smart agriculture* initiative, which focuses on empowering small-scale farmers. This approach predicts critical climate events, assesses their impacts and identifies coping strategies, thereby fostering participation in climate change mitigation and strengthening food security and livelihoods.

Nanotechnology further emerges as a catalyst for the agri-tech revolution, promising sustainable and efficient agricultural systems while bolstering food security (Lowry *et al.*, 2019; Neme *et al.*, 2021). Specifically, Lowry *et al.* (2019) assert that integrating nanotechnology into agriculture enhances the efficiency of light, water and soil management, enabling better adaptation to biotic and abiotic stressors. Neme *et al.* (2021) further elaborate on the multifaceted benefits of nanotechnology, including the development of NFs and efficient herbicides that boost agricultural productivity. In addition, it enhances food processing standards, improving nutritional quality and safety while extending shelf life through nanoparticles, thus reducing post-harvest losses.

3.5.2 Sustainable practices. Tariku and Kebede (2024) advocate for a range of strategies that include *integrated soil fertility management, small-scale irrigation, agroforestry, crop diversification and improved livestock feeding practices* to enhance agricultural sustainability. These approaches are vital for carbon sequestration, reducing emissions and building resilience against drought and heat. These practices support environmental health and ensure food security by minimising N_2O and CH_4 emissions while enhancing soil productivity. Trees play a critical role by capturing significant amounts of CO_2, contributing to agricultural resilience and productivity. Collectively, these efforts foster resilience to weather variability, provide alternative livelihoods, improve incomes and lead to increased productivity alongside reductions in GHG emissions.

Equally, Aryal *et al.* (2018) propose *site-specific nutrient management, crop diversification, minimum tillage and stress-resistant improved seed varieties*. Crop diversification, which incorporates legumes into rotations and intercropping, helps farmers mitigate risks while enhancing productivity and income through improved soil fertility and pest management. The adoption of stress-tolerant and high-yield varieties, such as drought-tolerant rice varieties like Swarna Sub 1, enables farmers to stabilise yields and increase incomes amid climate variability. Minimum tillage practices, including reduced tillage with residue retention, conserve soil moisture and allow for earlier planting of winter crops, enhancing overall resource efficiency. Site-specific nutrient management optimises nutrient use, further improving resource efficiency and reducing GHG emissions.

On the other hand, a groundbreaking study by Harvey *et al.* (2014) explored the design and management of *agricultural landscapes* to effectively adapt to and mitigate climate change impacts. The research revealed several key insights. Conserving and restoring riparian areas and wetlands is crucial for regulating water flows and sequestering carbon in peat and sediments. In addition, managing tree cover enhances biodiversity and ecosystem resilience. Sustainable land management practices to control flooding are essential for improving water holding capacity and infiltration rates. Furthermore, strategically placed windbreaks can protect crops and livestock from wind stress while reducing carbon loss due to soil erosion. Overall, the research emphasises the diversification of agricultural landscapes through strategies such as crop diversification, crop rotations, fallow lands, agroforestry and integrated mosaics of cropland and tree cover, promoting a holistic approach to sustainable agriculture.

4. Conclusions

The concept of CSA has emerged as a crucial response to the adverse effects of climate change on agricultural landscapes. This study categorises various CSA technologies and practices into five key areas: Climate-Smart Farming, Climate-Smart Irrigation, Climate-Smart Conservation, Climate-Smart Nutrition Management and Integrated CSA.

Recognising the diverse activities involved in agriculture, such as crop cultivation, livestock rearing and soil management, this categorisation essentially aims to provide a comprehensive understanding of how to achieve sustainable agriculture through CSA. Indeed, effective climate change mitigation requires an interconnected approach that integrates these CSA strategies, promoting both sustainability and environmental stewardship. Nonetheless, to successfully implement innovative technologies alongside traditional practices, active engagement from all stakeholders, including policymakers and farmers, is essential.

The findings of this study carry significant implications for climate policy, particularly in various countries. A detailed examination of existing CSA technologies and practices highlights the efforts made by different nations, providing policymakers with a well-organised overview of available options. This comprehensive discussion further illustrates how each approach can inform policymakers about the positive impacts of CSA, thereby assisting farmers in adopting relevant farming methods. Policymakers therefore can leverage these insights to design targeted interventions that support sustainable practices and enhance food security.

In conclusion, advocating for a sustainable agricultural landscape that considers environmental, economic and social factors is vital for strengthening agricultural resilience and achieving global food security. This study also identifies gaps in the literature, emphasising the need for empirical research on the long-term impacts of CSA practices and their effectiveness across different contexts. Future research should focus on comparative studies among regions, assessments of socioeconomic impacts and evaluations of policy frameworks that facilitate the adoption of CSA.

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