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ORIGINAL ARTICLE

Climate-smart agricultural practices for enhanced farm productivity, income, resilience, and greenhouse gas mitigation: a comprehensive review

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Abstract

This study reviews the literature published between 2013 and 2023 to comprehensively understand the consequences of adopting climate-smart agricultural (CSA) practices. We categorize the literature into three categories based on the scopes of climate-smart agriculture: (a) sustainably increase agricultural productivity and incomes; (b) adapt and build the resilience of people and agrifood systems to climate change; and (c) reduce or where possible, avoid greenhouse gas emissions. The review demonstrates that adopting CSA practices, in many instances, improves farm productivity and incomes. This increase manifests in increasing crop yields and productivity, income and profitability, and technical and resource use efficiency. Moreover, adopting CSA practices reinforces the resilience of farmers and agrifood systems by promoting food consumption, dietary diversity, and food security and mitigating production risks and vulnerabilities. Adopting CSA practices is environmentally feasible as it reduces greenhouse gas emissions and improves soil quality. An integrative strategy encompassing diverse CSA practices portends an optimized avenue to chart a trajectory towards agrifood systems fortified against climatic change.

Keywords Climate-smart agricultural practices · Effect evaluation · Technology adoption

JEL classification Q54 · Q16

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1 Introduction

The inevitable climate change events, such as frequent flooding, extreme heat, and uncertain precipitation patterns, have challenged crop production and agricultural growth (Carraro 2016; IPCC 2023). The detrimental effect of climate change on global crop production has been well documented (e.g., Challinor et al. 2014; Kuwayama et al. 2019; Lachaud et al. 2021; Miller et al. 2021; Schmitt et al. 2022). For example, the Latin America and the Caribbean study by Lachaud et al. (2021) showed that climate change reduces farm productivity by 9.03–12.7% in 2015–2050. Analyzing a half-decade panel dataset, Amale et al. (2022) demonstrated that delayed monsoon onset harms crop production in India.

The COVID-19 pandemic and burgeoning global population have notably surged food demand. As of 2020, global hunger afflicts around 720–811 million people (FAO). The advent of the COVID-19 pandemic has further exacerbated hunger and food insecurity. In addition, the global population is projected to surpass 9 billion by approximately 2037, primarily concentrated in low- and lower-middle-income countries. As highlighted by Lipper et al. (2014), a minimum of a 60% increase in agricultural production is imperative to cater to the expanding global populace's sustenance requirements. Ensuring the well-being of 9 billion people without hunger necessitates an augmentation in agrifood output while embracing sustainable development principles.

The detrimental ramifications of global climate change and the confluence of heightened agricultural production imperatives urge farmers to embrace climate-smart agricultural (CSA) practices that mitigate climate-induced adversities. A substantial body of literature has delved into the effects of climate-smart agriculture with a focus on different identified CSA practices (e.g., Adonadaga et al. 2022; Neuenschwander et al. 2023; Zizinga et al. 2022). For example, Fentie and Beyene (2019) found that adopting row planting amplifies maize yield and commercialization intensity in Ghana. Examining agricultural reduction prospects in South Asia, Aryal et al. (2020) highlighted that soil, water, and nutrient management practices can potentially mitigate greenhouse gas (GHG) emissions, contributing to climate change mitigation. Zizinga et al. (2022) conducted field experiments to scrutinize the efficacy of CSA practices, focusing on mulching at varying thicknesses (0, 2, 4, and 6 cm). They found that CSA practice adoption increases maize yield and water use efficiency, and the largest effect occurred at a 6 cm mulch depth. Nevertheless, these studies have focused on a single CSA practice, which may yield divergent outcomes across different locations.

As underscored by FAO (2021), climate-smart agriculture constitutes innovations aligned with three goals: (a) sustainably increase agricultural productivity and incomes; (b) adapt and build the resilience of people and agrifood systems to climate change; and (c) reduce or, where possible, avoid greenhouse gas emissions. Few studies have synthesized the literature regarding the impact of CSA adoption on the achievements of the three goals associated with the promotion of climate-smart agriculture (e.g., Dinesh et al. 2015; Hamidov et al. 2018; Jamil et al. 2023; Kaczan et al. 2013; Partey et al. 2018). For example, Dinesh et al. (2015) synthesized 19 CSA case studies, assessing the efficacy of interventions aligned with three CSA goals. Their analysis highlighted intervention effectiveness contingent on specific contexts. Hamidov et al. (2018) scrutinized 20 agricultural adaptation cases across Europe, gauging the influence of climate change adaptations on soil functions. Findings suggest that most adaptations enhance soil conditions, while their impact on biodiversity remains uncertain. Jamil et al. (2023) investigated CSA practices, including agroforestry, crop rotation, diversification, laser leveling, and advanced agronomic soil enhancement and water retention methods. They highlighted the importance of those practices in promoting climate adaptation.

The reviews mentioned above help enrich our understanding of the economic and environmental effects of CSA adoption and underscore the site-specific nature of climate change impacts on agricultural production. However, findings from selected practices or regions in those literature review studies lack generalizability. In addition, we cannot conclude a one-fit-all CSA (either row planting or adjusting crop calendars) for achieving the goal for other countries and regions. Thus, a comprehensive review of literature detailing CSA practices is imperative to discern effective CSA approaches for diverse crops and regions. Besides, achieving the three CSA objectives could result in synergies or trade-offs (e.g., Chavula 2021; Dinesh et al. 2015; Jagustović et al. 2021; Ogola and Ouko 2021; Tilahun et al. 2023). Yet, delineating effective CSA strategies for each goal is pivotal due to regional variations in prioritizing these goals. This distinction equips policymakers to craft targeted strategies and interventions aligned with their primary objectives.

The objective of the present study is to review a body of collected literature and summarize their findings on the effects of CSA adoption on farm productivity and incomes, resilience, and greenhouse gas emissions, covering the three goals of climate-smart agriculture. Our contributions to the existing literature encompass three aspects. Firstly, our review discerns the effects of CSA adoption based on the three goals intrinsic to climate-smart agriculture. This makes our study stand as one of the limited systematic syntheses of CSA-related literature. Secondly, we comprehensively delineate multiple dimensions to chart CSA adoption's impacts within each goal. Specifically, our analysis delves into the literature regarding the effects of CSA adoption on farm productivity and incomes, focusing on (1) crop yields and productivity, (2) incomes, and (3) technical and resource use efficiency – all aligning with CSA goal 1. In addition, we categorize the impacts of CSA adoption on resilience into (1) food consumption, dietary diversity, and food security and (2) production risk and vulnerability, which align with goal 2 of climate-smart agriculture. In the context of the goal 3, we examine impacts on (1) GHG emissions and (2) soil quality. Lastly, our study extends its purview to encompass diverse geographical locations, in contrast to the prevailing trend of concentrating on singular countries or regions. Encompassing Asia, Africa, Europe, and North America, our review enhances understanding and furnishes practical implications across varied landscapes.

The structure of this study unfolds as follows: In Section 2, we explain the procedure of literature collection and selection. Section 3 reviews the literature examining the effects of CSA adoption on farm productivity and incomes. Section 4 reviews the literature estimating the impact of CSA adoption on resilience, while Section 5 reviews the literature on the implications of CSA adoption for greenhouse gas emissions. Finally, we present concluding remarks in Section 6.

2 Literature collection and selection

This study employs the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines to comprehensively review the existing literature concerning the effects of CSA adoption. Adhering to the PRISMA methodology (Moher et al. 2015; Schaub et al. 2023), our approach entails a four-step process: defining the research question, locating pertinent literature based on established criteria, excluding non-relevant studies, and summarizing the findings to mitigate identification biases. To gather literature, online searches were conducted using Google Scholar, ScienceDirect, and Web of Science. Keywords including "*climate-smart agricultural practices*", "*impact of adopting climate-smart agricultural practices*", and "*effects of adopting climate-smart agricultural practices*" were employed. The article types include peer-reviewed journal articles, working papers, and reports. We screened articles from 2013 onwards and excluded those that did not focus on the impact of CSA adoption. The workflow is shown in Fig. 1.

In the first stage, 3,029 papers were identified, and the subsequent elimination of 537 duplicates resulted in a refined pool of 2,492 for screening based on titles and abstracts. In the second stage, applying exclusion criteria led to removing 1,846 papers not directly aligned with the specified search terms, narrowing the scope to 646. Following the exclusion of three inaccessible papers, a comprehensive assessment of the remaining 643 was conducted in the third step, emphasizing research design considerations and variable relevance. The final focus was honed on 107 papers, removing 536 irrelevant publications.

Among the selected articles, 60 scrutinize CSA adoption's impact on farm productivity. A total of 33 focused on income and resilience, respectively. A total of 25 articles focus on the effect of CSA adoption on GHG emissions (Fig. 2). The CSA practices are defined broadly in the selected papers. The identified practices include, such as adjusting crop

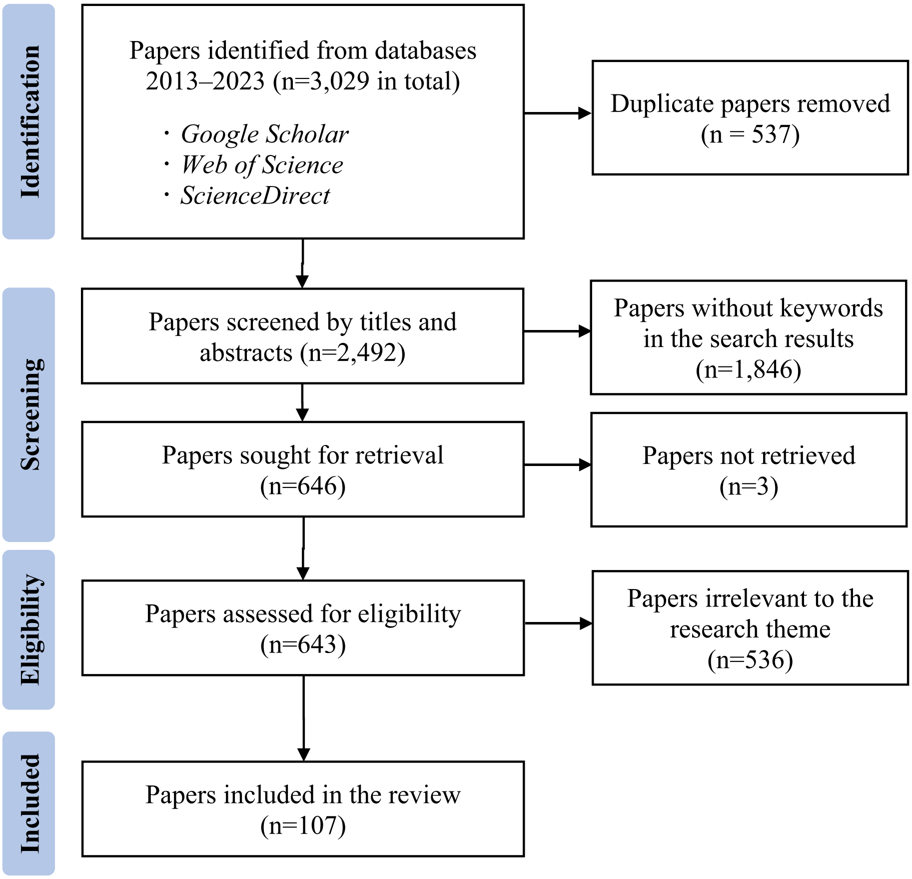

Fig. 1 Flow diagram of the literature selection

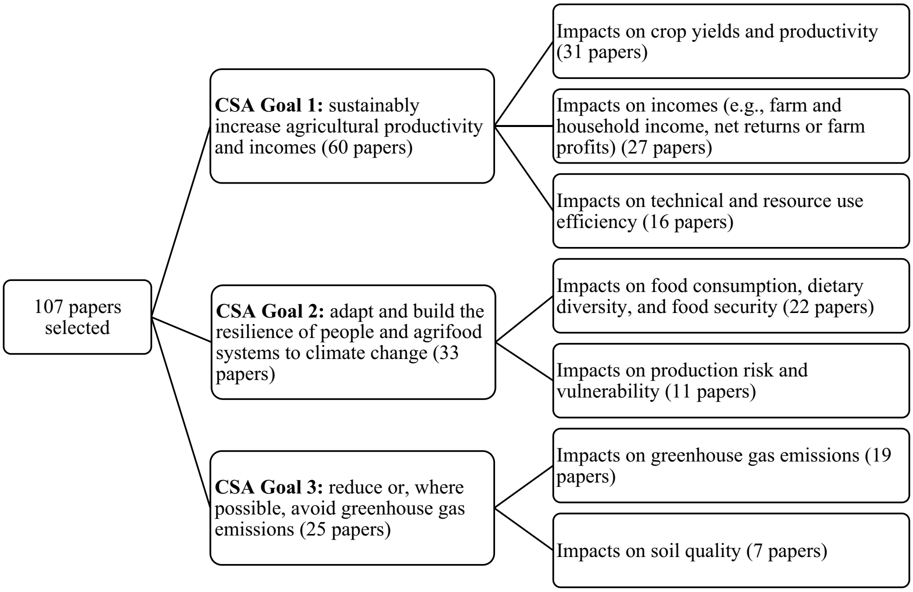

Fig. 2 Distributions of literature selection. Note: The reference may overlap across categories

calendars (Wang et al. 2022), adopting organic fertilizers and maize-legume intercropping (Maggio et al. 2022), and implementing row planting and drought-tolerant maize varieties (Martey et al. 2020). These practices, divergent from conventional agricultural methods, embody intelligence in adapting to climate change, collectively known as “climate-smart agriculture.”

3 Impacts of CSA adoption on farm productivity and incomes

The first CSA goal is to achieve sustainable increases in agricultural productivity and incomes. Prior research has extensively explored the direct influence of CSA adoption on indicators related to farm productivity and incomes. In addition, some studies have delved into the role of CSA adoption in enhancing both technical and resource use efficiency – a practical pathway for bolstering farm productivity and incomes.

3.1 Impacts on crop yields and productivity

We collected 31 studies investigating the influence of CSA adoption on crop yields and productivity (see Table 8 in the Appendix). These studies affirm a positive and statistically significant association between CSA adoption and crop yields or productivity. However, Gorst et al. (2018) presented an exception, demonstrating that adopting CSAs like altered crop timing, crop switching, and conservation technologies significantly boost rice productivity in Pakistan, while its impact on wheat productivity remains statistically insignificant. It is important to note that direct comparisons of the yields or productivity-enhancing effects across existing studies are inconvincible due to variations in CSA categories, crop types, and contextual settings. Nevertheless, the collective evidence supports the assertion that CSA adoption effectively contributes to a crucial facet of the first CSA objective – sustainable improvement of agricultural productivity.

The CSAs explored in the literature exhibit diversity across various countries and regions, complicating the identification of representative CSAs. Nonetheless, we have constructed a typology of five representative CSA groups, organized according to input management and crop production stages (see Table 1): (1) land and soil management. This group encompasses CSAs like minimum soil disturbance (Arslan et al. 2015), no-tillage Brouziyne et al. (2018), and laser land leveling (Ghosh 2019); (2) seed use. This category involves CSAs such as improved crop varieties (Xiong et al. 2014), disease/pest resistant varieties, and drought tolerant varieties (Makate et al. 2019; Martey et al. 2020); (3) chemical input use. Encompassing CSAs include adjusting chemical fertilizer use intensity (Kimaro et al. 2016), farm yard manure use (Khanal et al. 2018a), and integrated pest management (Midingoyi et al. 2019); (4) water management. This group comprises CSAs such as water absorption trenches (Amadu et al. 2020), adjusting irrigation frequency and amount (Khan et al. 2022), and having settling ponds (Do and Ho 2022); (5) crop calendars and rotations. Encompassing CSAs involve legume intercropping (Fao 2015), crop diversification (Khatri-Chhetri et al. 2016), and changing planting dates (Wang et al. 2022). It is important to note that this typology does not prescribe specific CSAs, as the effectiveness of CSA adoption hinges on contextual factors. However, it does offer a versatile toolkit that farmers can draw from when confronting new challenges posed by climate change.

In this category, few studies solely concentrate on one specific CSA. For example, Midingoyi et al. (2019) showed that fruit fly-integrated pest management increased mango production in Kenya. Wang et al. (2022) demonstrated that adjusting crop calendars enhances annual caloric yields in India and Bangladesh. Moreover, empirical literature underscores the amplified role of jointly adopting CSAs in elevating crop yields and productivity compared to singular CSA practice adoption. For example, Jamil et al. (2021) found that adopting irrigation and soil/crop management practices jointly impacts maize yield more in Pakistan than adopting only one.

Moreover, some studies have made efforts to identify the best combinations that help obtain the highest crop yields considering three or more CSAs (e.g., Arslan et al. 2015; Khanal et al. 2018b; Khatri-Chhetri et al. 2017; Muneer et al. 2023). For example, Arslan et al. (2015) found that adopting five CSAs, including minimum soil disturbance, crop rotation, legume intercropping, inorganic fertilizer, and improved seeds, contributes to the highest crop yields. Muneer et al. (2023) reported that jointly adopting the CSA practices, including encompassing modifications in cropping timing, shifting patterns, altering input use, soil and water conservation, income diversification, and infrastructure development, can generate the highest gains for farmers in Pakistan. The impact of climate change on agricultural production is multifaceted, with irregular precipitation patterns and shifting temperatures necessitating comprehensive attention to various aspects of crop cultivation (Zhou et al. 2023). Given this complexity, it is reasonable to emphasize joint CSA adoption, as its comprehensive approach is anticipated to substantially impact crop yields and productivity.

The literature within this category predominantly encompasses Asian (e.g., China, Vietnam, and Pakistan) and African countries (e.g., Uganda, Kenya, and Zimbabwe). A substantial portion of the population in these nations, particularly within rural areas, relies on agricultural production for income and sustenance. The imperative to adapt to climate change accentuates the priority of augmenting crop yields and productivity, propelling prior investigations into the effects of CSA adoption on these factors in these countries. In addition, the demand for grain-based sustenance significantly influences the crops under

Table 1 CSA groups that increase crop yields and productivity

Groups	Representative CSAs and corresponding references
Land and soil management	Minimum soil disturbance (e.g., Arslan et al. (2015); Fao (2015); Thierfelder et al. (2016); Branca et al. (2021)) No tillage/Zero tillage (e.g., Khatri-Chhetri et al. (2016); Brouziyne et al. (2018); Brouziyne et al. (2018); Ghosh (2019)) Laser land levelling (e.g., Khatri-Chhetri et al. (2016); Ghosh (2019); Ng'ang'a et al. (2021)) Reduced tillage (e.g., Kimaro et al. (2016); Khanal et al. (2018c); Branca et al. (2021)) Mulch (e.g., Kimaro et al. (2016); Zizinga et al. (2022)) Soil and water conservation practices (e.g., Arslan et al. (2017); Gorst et al. (2018); Khanal et al. (2018c); Makate et al. (2019); Branca et al. (2021); Kien et al. (2023); Muneer et al. (2023))
Seed use	Improved crop varieties (e.g., Xiong et al. (2014); Arslan et al. (2015); Abid et al. (2016); Khatri-Chhetri et al. (2016); Arslan et al. (2017); Gorst et al. (2018); Khanal et al. (2018c); Ghosh (2019); Makate et al. (2019); Jamil et al. (2021); Ng'ang'a et al. (2021); Khan et al. (2022)) Disease/pest resistant varieties (e.g., Khanal et al. (2018a)) Drought tolerant varieties (e.g., Makate et al. (2019); Khanal et al. (2018c); Makate et al. (2019); Bairagi et al. (2020); Martey et al. (2020); Dey et al. (2023)) Grow flood tolerant varieties (e.g., Khanal et al. (2018c); Bairagi et al. (2020)) Genetic improvements (e.g., Sun et al. (2018))
Chemical input use	Application of chemical/inorganic fertilizer (e.g., Xiong et al. (2014); Arslan et al. (2015); Abid et al. (2016); Kimaro et al. (2016); Arslan et al. (2017); Ariani et al. (2018); Khanal et al. (2018c); Khan et al. (2022)) Organic fertilizers (e.g., Arslan et al. (2017); Khanal et al. (2018c); Scognamillo and Sitko (2021)) Organic matter amendment (e.g., Ariani et al. (2018))
Water management	Soil and water conservation practices (e.g., Arslan et al. (2017); Gorst et al. (2018); Khanal et al. (2018c); Makate et al. (2019); Branca et al. (2021); Kien et al. (2023); Muneer et al. (2023)) Water absorption trenches (e.g., Amadu et al. (2020)) Adjusting irrigation frequency and amount (e.g., Khan et al. (2022); Ariani et al. (2018); Khanal et al. (2018c); Jamil et al. (2021); Kien et al. (2023)) Having settling ponds (e.g., Do and Ho (2022)) Oil and water conservation structures (e.g., Scognamillo and Sitko (2021)) Upgrading pond dikes (e.g., Do and Ho (2022)) Lining ponds with plastic sheets (e.g., Do and Ho (2022)) Drill the deep well (e.g., Khan et al. (2022))
Crop calendars and rotation	Crop rotation (e.g., Arslan et al. (2015); Fao (2015); Thierfelder et al. (2016); Ng'ang'a et al. (2021)) Legume intercropping (e.g., Arslan et al. (2015); Fao (2015); Kimaro et al. (2016); Arslan et al. (2017); Scognamillo and Sitko (2021)) Changing planting dates (e.g., Abid et al. (2016); Brouziyne et al. (2018); Khan et al. (2022); Wang et al. (2022); Muneer et al. (2023)) Crop diversification (e.g., Khatri-Chhetri et al. (2016)) Crop residue retention (e.g., Thierfelder et al. (2016); Branca et al. (2021)) Alterations in crop timing (e.g., Gorst et al. (2018); Martey et al. (2020); Khan et al. (2022)) Change planting location of varieties (e.g., Khanal et al. (2018c)) Agronomic management (e.g., Sun et al. (2018); Jamil et al. (2021); Muneer et al. (2023))
Others	Fruit fly integrated pest management (e.g., Midingoyi et al. (2019)) Agroforestry (e.g., Amadu et al. (2020); Branca et al. (2021); Khan et al. (2022)) Weather advisory (e.g., Bairagi et al. (2020)) Buy insurance (e.g., Khan et al. (2022); Dey et al. (2023)) Permanent planting basins (e.g., Zizinga et al. (2022)) Infrastructure development (e.g., Muneer et al. (2023))

The references in the table are rearranged from Table 8 in the Appendix examination. Within this domain, 24 studies concentrated on the relationship between CSA adoption and the yields or productivity of grain crops such as rice, maize, and wheat, collectively accounting for 77.4% of the reviewed studies. Conversely, few papers explore the ramifications of CSA adoption on oil-bearing and cash crops like cotton (Jamil et al. 2021) and cereal and legume crops (Makate et al. 2019). Studies also analyze fruit crops like mango (Midingoyi et al. 2019) and fisheries such as shrimp (Do and Ho 2022).

3.2 Impacts on incomes

Another facet of the first CSA goal involves the sustainable enhancement of income. It is imperative to scrutinize the effects of CSA adoption on income-related indicators, such as income, net returns, and profit. While the augmentation of crop yields and productivity primarily bolsters food supply, aiding rural residents in averting hunger, the elevation in income possesses the potential to mitigate poverty. Moreover, it empowers rural residents to access a broader spectrum of food varieties beyond those they cultivate.

We have collected 27 papers exploring CSA adoption's impact on income-related indicators. Some studies exclusively focused on one or two CSAs. For example, Fentie and Beyene (2019) found that row planting adoption increases teff income in Ethiopia. Similarly, Song et al. (2018) showed that adopting irrigation and drainage improved grain net profit in China. Conversely, most of the literature has examined the simultaneous adoption of multiple CSAs, which is anticipated to yield a greater income increase than a single adoption. For example, Khatri-Chhetri et al. (2016) found that adopting four identified CSAs, including improved crop varieties, crop diversification, laser land leveling, and zero tillage practice, increases rice and wheat production incomes in India. In another study, Belay et al. (2023) investigated the role of seven CSAs, such as soil and water conservation with biological measures, crop rotation, improved crop varieties, agroforestry systems, improved breeds, and residue incorporation in enhancing the income of farmers in Ethiopia. They confirmed the positive relationship between CSA practice adoption and income growth.

The examined indicators comprise (1) crop income or gross revenue (Khatri-Chhetri et al. 2016; Imran et al. 2018); (2) farm income (Scognamillo and Sitko 2021); (3) household income (Makate et al. 2019; Chiputwa et al. 2022); (4) net returns, net income, or profit (defined as the difference between gross revenue and production costs) (Jamil et al. 2021; Dey et al. 2023); (5) net household income (Brüssow et al. 2017; Kien et al. 2023); (6) other indicators like net present values (Mutenje et al. 2019) and farm assets (Danso-Abbeam and Baiyegunhi 2018). The details are presented in Table 2. Although crop income or household income provide insights, they do not encompass production costs or household expenditures (Zheng et al. 2021a). Therefore, incorporating net returns or net household income is valuable for a comprehensive assessment of the income-enhancing impact of CSA adoption.

Findings in this category also underscore the importance of utilizing indicators like net returns or net household income (see Table 9 in the Appendix). When crop income, farm income, or household income are employed as outcome variables, prevailing studies consistently reveal that adopting various CSA combinations yields a positive and statistically significant impact on these variables (Abid et al. 2016; Imran et al. 2018; Makate et al. 2019; Ogada et al. 2020), suggesting the economic viability of CSA adoption. Nevertheless, the efficacy of CSA adoption is contingent upon considering production costs or household expenditures. For example, net returns or net farm income is the disparity between crop/farm gross revenue and production costs. Net household income is derived from the contrast between total household income and expenditure. Several studies revealed that CSA adoption contributes to

Table 2 CSA groups that increase income-related indicators

Indicators	Representative CSAs and corresponding references
Crop income/gross revenue	Land and soil management: Minimum soil disturbance (e.g., Arslan et al. (2015); Fao (2015); Thierfelder et al. (2016); Branca et al. (2021)); Laser land levelling (e.g., Khatri-Chhetri et al. (2016); Imran et al. (2018)); Zero tillage (e.g., Khatri-Chhetri et al. (2016)); Minimum tillage (e.g., Imran et al. (2018)) Seed use: Improved crop varieties (e.g., Abid et al. (2016); Khatri-Chhetri et al. (2016); Imran et al. (2018); Belay et al. (2023)); Chemical input use: Adjust fertilizer types (e.g., Abid et al. (2016); Imran et al. (2018); Scognamillo and Sitko (2021)) Water management: Canal irrigation (e.g., Kien et al. (2023)); Soil and water conservation strategies (e.g., Belay et al. (2023); Kien et al. (2023)); Drainage management (e.g., Imran et al. (2018)); Raising crops on bed (e.g., Imran et al. (2018)) Crop calendars and rotation: Changing planting dates (e.g., Abid et al. (2016)); Crop diversification (e.g., Khatri-Chhetri et al. (2016)); Crop rotation (e.g., Imran et al. (2018); Belay et al. (2023)); Row planting (e.g., Fentie and Beyene (2019)); Intercrop (e.g., Scognamillo and Sitko (2021); Belay et al. (2023))
Farm income	Seed use: Improved crop (e.g., Teklewold et al. (2017); Makate et al. (2019)) Chemical input use: Fertilizer (e.g., Teklewold et al. (2017)); Pesticides combination (e.g., Danso-Abbeam and Baiyegunhi (2018)) Water management: Agricultural water management (e.g., Teklewold et al. (2017))
Household income	Seed use: Improved crop (e.g., Makate et al. (2019); Ogada et al. (2020)) Water management: Soil and water conservation strategies (e.g., Brüssow et al. (2017); Ogada et al. (2020)) Crop calendars and rotation: Adjustments to farm and crop management (e.g., Brüssow et al. (2017)); Livestock production systems (e.g., Brüssow et al. (2017); Zhao et al. (2019); Ogada et al. (2020))
Net return/net income/profit	Land and soil management: Crop residue management (e.g., Kakraliya et al. (2018)); Nutrient management (e.g., Kakraliya et al. (2018)); Laser land levelling (e.g., Ghosh (2019)); Zero tillage (e.g., Ghosh (2019)); Mulching (e.g., Ojo and Baiyegunhi (2020)) Seed use: Improved crop (e.g., Sain et al. (2017); Mutenje et al. (2019); Ghosh (2019); Bairagi et al. (2020); Onyeneke et al. (2020); Dey et al. (2023)) Chemical input use: Pest management (e.g., Midingoyi et al. (2019); Bairagi et al. (2020)); Fertilizer (e.g., Ojo and Baiyegunhi (2020)) Water management: Contour ditches (e.g., Sain et al. (2017)); Stone barriers (e.g., Sain et al. (2017)); Water reservoirs (e.g., Sain et al. (2017); Onyeneke et al. (2020)); Irrigation (e.g., Sain et al. (2017); Song et al. (2018); Onyeneke et al. (2020); Jamil et al. (2021)); Drainage management (e.g., Song et al. (2018)); Soil and water conservation techniques (e.g., Ojo and Baiyegunhi (2020); Jamil et al. (2021)) Crop calendars and rotation: Crop rotation (e.g., Sain et al. (2017); Mutenje et al. (2019)); Crop intercrop (e.g., Mutenje et al. (2019)); Livestock production systems (e.g., Ojo and Baiyegunhi (2020)); Mixed cropping (e.g., Ojo and Baiyegunhi (2020)); Mono-cropping (e.g., Ojo and Baiyegunhi (2020)); Crop diversification (e.g., Onyeneke et al. (2020)); Intensification system (e.g., Dey et al. (2023))
Net household income	Canal irrigation (e.g., Kien et al. (2023)) Agricultural conservation practices (e.g., Kien et al. (2023))

Table 2 (continued)

Indicators	Representative CSAs and corresponding references
Others (e.g., Productive farm assets, Asset index, Income index)	Productive farm assets: Pesticides combination (Danso-Abbeam and Baiyegunhi (2018)) Asset index: Soil and water conservation strategies, livestock production systems, improved crop and agroforestry (Ogada et al. (2020)) Income index: Laser land leveler, green seeker, multi-crop planter, harvester and thresher, zero tillage, leaf color chart, nutrient expert tool, relay planter and bed planter Agarwal et al. (2022)

The references in the table are rearranged from Table 9 in the Appendix

an increase in net returns (Ghosh 2019), net farm income (Teklewold et al. 2017; Kakraliya et al. 2018), or household net income (Brüssow et al. 2017; Kien et al. 2023). However, Song et al. (2018) exhibited that engineering-type measures have negligible influence on crop net profit in China, while Quddoos et al. (2022) emphasized that effective climate change adaptation measures could still lead to a 4.4% profit reduction for farms in Austria.

Both grain crops (such as wheat and rice) and cash crops (like cotton and fruit) contribute to increased household income, with the latter often playing a more substantial role due to its commercialization. As such, the literature analyzing the relationship between CSA adoption and income-related indicators encompasses both grain and cash crops, differing slightly from the literature assessing the impact of CSA adoption on crop yields and productivity in the preceding subsection. For example, this subsection examines crops like wheat (Abid et al. 2016; Khatri-Chhetri et al. 2016), rice (Bairagi et al. 2020; Dey et al. 2023), teff (Fentie and Beyene 2019), and grain (Song et al. 2018). Simultaneously, existing studies concentrate on cash crops like cotton (Imran et al. 2018; Jamil et al. 2021), cocoa (Danso-Abbeam and Baiyegunhi 2018), mango (Midingoyi et al. 2019).

3.3 Impacts on technical and resource use efficiency

In addition to directly analyzing the impact of CSA adoption on farm productivity and income indicators, some studies have investigated the effective pathways through which CSA adoption enhances farm productivity and incomes. One example is enhancing technical and resource use efficiency, allowing rural households to achieve greater output with consistent production inputs. Technical efficiency refers to the ratio of farmers' observed output to the maximum achievable output given the existing inputs, reflecting the utilization efficiency of various agricultural inputs (Zheng et al. 2021b). In this subsection, we focus on the literature examining the effects of CSA adoption on technical and resource use efficiency.

A total of 16 papers were collected to examine the impact of CSA adoption on efficiency-related indicators (see Table 3). Among them, seven studies focused on the relationship between CSA adoption and technical efficiency (e.g., Imran et al. 2019; Khanal et al. 2018b; Pangapanga-Phiri and Mungatana 2021), which reflects the efficiency of utilizing agricultural input combinations. They consistently found that CSA adoption increases technical efficiency in crop production in countries like Nepal (Khanal et al. 2018b), Pakistan (Imran et al. 2019), and Malawi (Pangapanga-Phiri and Mungatana 2021). In addition, seven papers analyzed the efficiency of water utilization. For example, Çetin and Kara (2019) studied the effect of adopting surface and subsurface drip irrigation on water productivity in Turkey, reporting an increase in water productivity. Wang et al. (2022) demonstrated that adjusting crop calendars reduces the blue water requirement in India and Bangladesh. In addition, adopting various CSA practices has also enhanced energy productivity in India (Kakraliya et al. 2018) and land economic productivity in Turkey (Çetin and Kara 2019). In conclusion, existing evidence supports the notion that adopting CSA practices is an effective strategy for increasing technical and resource use efficiency, thereby contributing to achieving the first CSA goal of sustainable farm productivity and income enhancement.

4 Impacts of CSA adoption on resilience

The second goal of CSA is to enhance the adaptability and resilience of both people and agrifood systems to the effects of climate change. Resilience can be understood from various perspectives, such as psychology, sociology, and biological disciplines (Herrman et al. 2011), resulting in a lack of consensus on its operational definition. Our review of existing literature indicates that many CSA-related studies primarily focus on enhancing physical resilience among individuals. This involves improving physical health by increasing food consumption, dietary diversity, and food security (e.g., Bazzana et al. 2022; Hasan et al. 2018; Teklewold et al. 2019). Thus, we examine the literature examining the impact of CSA adoption on food-related indicators. In addition, the resilience of agrifood systems pertains to their ability to address potential risks and mitigate vulnerabilities. Consequently, we then delve into the literature discussing the effects of CSA adoption on production risk and vulnerability.

4.1 Impacts on food consumption, dietary diversity, and food security

We have collected 22 papers that analyze the influence of CSA adoption on food consumption, dietary diversity, and food security. As summarized in Table 4, food consumption is assessed through metrics such as food consumption expenditure (Danso-Abbeam and Baiyegunhi 2018; Hasan et al. 2018) or weighted food consumption score (Brüssow et al. 2017; Egeru et al. 2022). Dietary diversity refers to the variety of food items (typically across 12 categories) consumed by a household within a specified period (usually three or seven days) (Ma et al. 2022). Food security is commonly gauged using subjective measurements (Danso-Abbeam and Baiyegunhi 2018), a weighted score (Agarwal et al. 2022; Dey et al. 2023), or specific metrics (Bazzana et al. 2022). Some studies employed a reverse perspective, considering food insecurity scores (Hasan et al. 2018; Issahaku and Abdulai 2020a) or the food insecurity experience scale (Ali et al. 2022). In addition, our analysis incorporates indicators like food availability (Lopez-Ridaura et al. 2018; Teklewold et al. 2019) and human health (Midingoyi et al. 2019).

Existing studies consistently demonstrate that adopting various CSA practices significantly increases food consumption and expenditure (see Table 10 in the Appendix). For example, Fentie and Beyene (2019) observed that row planting significantly elevated teff consumption per capita in Ethiopia. Egeru et al. (2022) evidenced that multiple CSA adoptions notably enhanced food consumption scores in Uganda. However, the impact of CSA adoption on dietary diversity is not uniform. Hasan et al. (2018) emphasized the lack of significant effects of multiple CSA adoption on household dietary diversity scores in Bangladesh. In contrast, studies in Ghana (Issahaku and Abdulai 2020a) and Ethiopia (Teklewold et al. 2019; Cholo et al. 2019; Ali et al. 2022) reported a positive relationship between CSA adoption and household dietary diversity.

Table 3 Overview of literature analyzing the impact of CSA adoption on technical and resource use efficiency

References	Country	CSAs	Outcomes and influence
Brouziyne et al. (2018)	Morocco	No tillage, early sowing	Crops water productivities (Winter wheat & Sunflower)
Salat and Swallow (2018)	Kenya	Residue management, intercrop, distance, radio, plough	Technical Efficiency (+)
Kakraliya et al. (2018)	India	Crop residue management, nutrient management, nutrient management, ICTs, crop insurance	System productivity (+) Total water productivity (+) Energy productivity (+)
Khanal et al. (2018b)	Nepal	Grow drought tolerant varieties, grow short duration varieties, grow disease/pest resistant varieties, grow flood tolerant varieties, change planting location of varieties, increase seed rate, cultivation of direct seeded rice, change sowing/planting/harvesting date, seed priming, improve/increase irrigation, construction of water ways during heavy rainfall, reduce tillage, increasing number of weeding, soil conservation techniques, improve/increase chemical fertilizer use, improve/increase farm yard manure use, use more pesticides	Technical efficiency (+)
Çetin and Kara (2019)	Turkey	Surface drip irrigation, subsurface drip irrigation	Water productivity (+) Economic water productivity (+) Land economic productivity (+)
Ho and Shimada (2019)	Vietnam	Changing area of farming land, soil conservation, income diversification, changing irrigation schedule, diversifying crop, changing crop variety, changing fertilizer and chemical use, reducing the number of crop plantings, changing sowing or harvesting date	Technical efficiency of rice production (+)
Imran et al. (2019)	Pakistan	Raising crops on bed, laser land levelling, conjunctive use of water, drainage management, minimum tillage, integrated Pest Management, crop rotation, and improved crop varieties	Technical efficiency (+) Economic efficiency (+) Water use efficiency (+)

Table 3 (continued)

References	Country	CSAs	Outcomes and influence
Tong et al. (2019)	China	Crop rotations (CR), conservation tillage (CT), crop insurance (CI)	Technical efficiency (+) (CR, CT) Technical efficiency (NS) (CI)
Bijarniya et al. (2020)	India	Reduced tillage with residue, recommended dose of fertilizer, zero tillage with residue, green seeker, tensiometer, information, communication technology, crop insurance	Energy-use-efficiency (+)
Bostian et al. (2020)	Finland	Manure injection and herbicide reduction	Technical efficiency (–)
Mujeyi and Mudhara (2021)	Zimbabwe	Intercropping, sole CN, rotation, minimum tillage, drought-tolerant maize, manure use, mulching	Profit efficiency (+) (maize-growing farmers)
Mishra et al. (2021)	Thailand and Vietnam	System of rice intensification	Efficiency of mineral fertilizer (+)
Pangapanga-Phiri and Mungatana (2021)	Malawi	Organic manure, soil and water conservation, maize improved varieties, legume intercropping, cushion maize production	Technical efficiency (+)
Kakraliya et al. (2022)	India	Laser land levelling, zero tillage, direct-seeded rice, site-specific nutrient management, precision irrigation management	Energy use efficiency (+)
Wang et al. (2022)	India and Bangladesh	Adjusting crop calendars	Blue water requirement (–)
Zizinga et al. (2022)	Uganda	Half-moon, mulching, permanent planting basins	Water use efficiency (+)

Positive and statistically significant impact (+); Negative and statistically significant impact (–); No statistically significant impact (NS)

Table 4 CSA groups that increase food consumption, dietary diversity, and food security

Indicators	Representative CSAs and corresponding references
Food consumption/food consumption score/food expenditure	Land and soil management: Minimum soil disturbance (e.g., Arslan et al. (2015); Fao (2015); Thierfelder et al. (2016); Branca et al. (2021)); Soil and water conservation strategies (e.g., Brüssow et al. (2017); Belay et al. (2023)); Field management (e.g., Brüssow et al. (2017); Egeru et al. (2022)); Soil fertility management (e.g., Ali et al. (2022)); Mulching (e.g., Egeru et al. (2022)); Residue incorporation (e.g., Belay et al. (2023)); Conservation agriculture (e.g., Lopez-Ridaura et al. (2018); Issahaku and Abdulai (2020a); Ali et al. (2022); Egeru et al. (2022)) Seed use: Improved crop varieties (e.g., Hasan et al. (2018); Issahaku and Abdulai (2020a); Martey et al. (2020); Egeru et al. (2022); Belay et al. (2023)); Seed storage (e.g., Hasan et al. (2018)) Chemical input use: Fertilizers (e.g., Hasan et al. (2018); Egeru et al. (2022)); Pest management (e.g., Egeru et al. (2022)) Water management: Rainwater harvesting (e.g., Hasan et al. (2018); Egeru et al. (2022)); Irrigation (e.g., Ali et al. (2022); Egeru et al. (2022)) Crop calendars and rotation: Land rotation (e.g., Issahaku and Abdulai (2020a); Egeru et al. (2022); Belay et al. (2023)); Mixed-cropping (e.g., Issahaku and Abdulai (2020a); Egeru et al. (2022)); Row planting (e.g., Martey et al. (2020)); Crop management (e.g., Brüssow et al. (2017)); Improved livestock husbandry (e.g., Lopez-Ridaura et al. (2018); Ali et al. (2022)); Crop diversity (e.g., Ali et al. (2022)); Intercropping (e.g., Egeru et al. (2022))
Food diversity	Land and soil management: Sustainable land management (e.g., Cholo et al. (2019)); Soil and water conservation strategies (e.g., Teklewold et al. (2019)); Conservation tillage (e.g., Issahaku and Abdulai (2020a); Ali et al. (2022)); Soil fertility management (e.g., Ali et al. (2022)) Seed use: Improved crop varieties (e.g., Danso-Abbeam and Baiyegunhi (2018); Hasan et al. (2018); Teklewold et al. (2019); Issahaku and Abdulai (2020a)); Seed storage (e.g., Hasan et al. (2018)) Chemical input use: Fertilizer (e.g., Danso-Abbeam and Baiyegunhi (2018); Hasan et al. (2018); Teklewold et al. (2019)); Pest management (e.g., Danso-Abbeam and Baiyegunhi (2018)) Water management: Rainwater harvesting (e.g., Hasan et al. (2018)); Soil and water conservation strategies (e.g., Teklewold et al. (2019)) Crop calendars and rotation: Crop diversity (e.g., Teklewold et al. (2019); Ali et al. (2022)); Land rotation (e.g., Issahaku and Abdulai (2020a)); Mixed-cropping (e.g., Issahaku and Abdulai (2020a)); Improved livestock husbandry (e.g., Ali et al. (2022))
Food security	Land and soil management: Soil and water conservation (e.g., Douxchamps et al. (2016); Brüssow et al. (2017); Bazzana et al. (2022)); Field management (e.g., Marchant (2017); Brüssow et al. (2017)); Soil management practices (e.g., Marchant (2017)); Sustainable land management (e.g., Cholo et al. (2019)); Mulching (e.g., Dadzie et al. (2020)); Conservation tillage (e.g., Oyawole et al. (2020); Bazzana et al. (2022); Agarwal et al. (2022)); Laser land leveler (e.g., Agarwal et al. (2022)) Seed use: Improved crop varieties (e.g., Douxchamps et al. (2016); Danso-Abbeam and Baiyegunhi (2018); Dadzie et al. (2020); Dey et al. (2023)) Chemical input use: Fertilizers (e.g., Douxchamps et al. (2016); Danso-Abbeam and Baiyegunhi (2018); Oyawole et al. (2020); Abegunde et al. (2022)); Pest management (e.g., Danso-Abbeam and Baiyegunhi (2018)) Crop calendars and rotation: Row planting (e.g., Fentie and Beyene (2019)); Crop rotation (e.g., Dadzie et al. (2020); Issahaku and Abdulai (2020a); Oyawole et al. (2020); Abegunde et al. (2022)); Crop diversity (e.g., Douxchamps et al. (2016); Arslan et al. (2016); Dadzie et al. (2020)); Crop management (e.g., Marchant (2017); Brüssow et al. (2017)); Crop-livestock management (e.g., Abegunde et al. (2022))

Table 4 (continued)

Indicators	Representative CSAs and corresponding references
Food insecurity	Land and soil management: Conservation tillage (e.g., Issahaku and Abdulai (2020a); Ali et al. (2022); Bazzana et al. (2022)); Soil fertility management (e.g., Ali et al. (2022)); Soil and water conservation strategies (e.g., Bazzana et al. (2022)) Seed use: Improved crop varieties (e.g., Hasan et al. (2018); Issahaku and Abdulai (2020a)); Seed storage (e.g., Hasan et al. (2018)) Chemical input use: Fertilizers (e.g., Hasan et al. (2018)) Water management: Rainwater harvesting (e.g., Hasan et al. (2018)); Soil and water conservation strategies (e.g., Bazzana et al. (2022)) Crop calendars and rotation: Crop management(e.g., Hasan et al. (2018); Ali et al. (2022)); Land rotation (e.g., Issahaku and Abdulai (2020a)); Mixed-cropping (e.g., Issahaku and Abdulai (2020a)); Improved livestock husbandry (e.g., Ali et al. (2022))
Others (e.g., human health, calorie and protein availability)	Human health: pest management, Midingoyi et al. (2019) Improves calorie and protein availability: Crop diversification, soil and water conservation, and modern inputs, Teklewold et al. (2019)

The references in the table are rearranged from Table 10 in the Appendix

Regarding the impact of CSA adoption on food security indicators, the existing literature consistently supports that CSA adoption increases food security (Brüssow et al. 2017; Cholo et al. 2019; Dadzie et al. 2020; Oyawole et al. 2020; Abegunde et al. 2022) or reduces food instability and insecurity (Issahaku and Abdulai 2020a; Bazzana et al. 2022). However, Hasan et al. (2018) found no significant influence of multiple CSA adoption on household insecurity access scores in Bangladesh. In addition, in Kenya, Midingoyi et al. (2019) analyzed the impact of integrated pest management on human health, a more comprehensive indicator of people's physical resilience. They established a positive relationship between integrated pest management and human health.

4.2 Impacts on production risk and vulnerability

CSA adoption could enhance agrifood systems' resilience by improving their ability to manage risks and reduce vulnerability. Around 11 of our reviewed studies have assessed CSA adoption's impact on production risk and vulnerability (see Table 5). These risk-related indicators include the expected error term, estimated through a moment-based production function (Zheng and Ma 2023), and its variance, skewness, and kurtosis (Wang et al. 2018; Shahzad and Abdulai 2020; Sarr et al. 2021). Vulnerability, reflecting the capacity of agrifood systems to anticipate and recover from climate change impacts (Wouterse et al. 2022), lacks a consistent concept (Adonadaga et al. 2022). Arslan et al. (2018) employed the logarithm of income per capita and the probability of falling below the poverty line as vulnerability metrics. Adonadaga et al. (2022) defined drought vulnerability using four components: threshold capacity, coping capacity, recovery capacity, and adaptive capacity.

The literature examining the impact of CSA adoption on production risk focuses on grain crops such as rice (Wang et al. 2018), maize (Issahaku and Abdulai 2020b), and wheat (Komarek et al. 2019). For example, Wang et al. (2018) demonstrated that irrigation practices significantly increase rice yield and reduce variance, decreasing risk exposure. This aligns with Issahaku and Abdulai (2020b), who observed that improved extension services increase crop revenue and risk exposure (skewness of crop yield) in Ghana. In Tanzania,

Table 5 Overview of literature analyzing the impact of CSA adoption on production risk and vulnerability

References	Country	CSA	Outcomes and influence
Di Falco and Veronesi (2014)	Ethiopia	Climate change adaption strategies	Downside risk exposure (skewness) (+)
Huang et al. (2015)	China	No till, reduced tillage, cover crop, biochar	Risk of rice yield (–)
Wang et al. (2018)	China	Irrigation practices	Skewness (Downside risk exposure) (–) Rice yield (+) Variance (–)
Arslan et al. (2018)	Zambia	Livelihood diversification	Vulnerability (–)
Shahzad and Abdulai (2020)	Pakistan	Changing input mix, changing cropping calendars, variety diversification, soil and water conservation, improved seed varieties, crop rotation, crop diversification, off-farm income, and migration	Net returns (+) Volatility of farm net returns (–) Farmers' exposure to downside risk (–)
Issahaku and Abdulai (2020b)	Ghana	Crop choice and soil and water conservation measures	Exposure to risks (skewness of crop yield) (+) Crop revenue (+) (maize, rice, millet, sorghum, groundnut, yam, cassava, vegetables)
Sarr et al. (2021)	Tanzania	System of rice intensification	Expected yields (+) Yield variance (NS) Yield skewness (exposure to downside risk) (–) (Rice)
Alemaw and Simalenga (2015)	Sub-Saharan Africa	Improving soil water productivity, improved water harvesting	Risk (–) Resilience (+) Reliability (–) (maize, sunflower, and sorghum)
Adonadaga et al. (2022)	Ghana	Improving and sustaining the quality of water, availability of water for domestic and agricultural purposes	Vulnerability to drought (–)
Teklu et al. (2022)	Ethiopia	Soil and water conservation, improved variety, rotation, compost, row planting, agroforestry	Livelihood vulnerability (–)
Ali et al. (2023)	Ethiopia	Integrated soil fertility management, conservation agriculture, crop diversification, agroforestry, and soil and water conservation	Vulnerability indices (–)

Positive and statistically significant impact (+); Negative and statistically significant impact (–); No statistically significant impact (NS)

Sarr et al. (2021) determined that the system of rice intensification significantly enhances expected yields and yield skewness while yield variance remains relatively unchanged. In addition, Shahzad and Abdulai (2020) considered kurtosis, the fourth moment, and revealed that adopting climate-smart farming contributes to decreased kurtosis, indicating reduced production risk. These findings in this literature strand extend the evidence summarized in Section 3.1, highlighting that CSA adoption increases crop yields and productivity, significantly mitigates production risk, and stabilizes crop yields and net returns.

We identified four papers that explore the relationship between CSA adoption and vulnerability. Arslan et al. (2018) discovered that diversification of crops, livestock, and income significantly increases per capita income and decreases the probability of falling below the poverty line in rural Zambia. This underscores the importance of diversification strategies in reducing vulnerability. In contrast, Adonadaga et al. (2022) emphasized the ongoing challenge of reducing vulnerability to drought in Ghana due to difficulties in implementing adaptation strategies. In Ethiopia, Teklu et al. (2022) demonstrated that adopting soil and water conservation, improved varieties, crop rotation, composting, row planting, and agroforestry decreases livelihood vulnerability. Similarly, Ali et al. (2023) reported that adopting multiple CSAs reduces vulnerability indices.

5 Impacts of CSA adoption on greenhouse gas emissions

The third CSA goal is to mitigate GHG emissions when possible. Agriculture, forestry, and land use collectively contributed 18.4% of global GHG emissions in 2020 (Ritchie and Roser 2020). Notably, agricultural production is a major emission source within the agrifood systems, with crop and livestock activities within the farm gate accounting for approximately 142Tg CH4 and 8.0Tg N2O annually in 2007–2016 (FAO 2020). Thus, promoting CSA adoption is crucial to mitigate GHG emissions from agricultural production. This section first reviewed literature exploring the direct relationship between CSA adoption and GHG emissions. In addition, it is vital to consider GHG emissions arising from land use and changes like deforestation and peatland degradation, which are linked to agriculture in various regions and account for 5–14% of total GHG emissions (FAO 2020). For this reason, we also discuss existing studies on the impact of CSA adoption on soil quality.

5.1 Impacts on GHG emissions

We reviewed 19 papers that analyze the impact of CSA adoption on GHG emissions (see Table 6). Most studies in this strand have quantified the impact of CSA adoption on reducing GHG emissions. Some specifically highlight the negative impact of adopting various CSA practices. For example, McNunn et al. (2020) found that adopting crop rotations, tillage practices, stover removal practices, cover crops, and nitrogen timing decreases GHG emissions in the United States. Teklu et al. (2022) showed that adopting soil and water conservation, improved varieties, crop rotation, composting, row planting, and agroforestry reduces GHG emissions in Ethiopia. In addition, several studies have estimated the extent of the reduction effect from CSA adoption. For example, Ariani et al. (2018) indicated that adopting practices like leaf color charts for applying *N* fertilizer, paddy soil test kits for determining basic fertilizer, organic matter amendment, and intermittent irrigation could reduce the global warming potential of GHGs by 7%–23%. Iqbal et al. (2023) demonstrated that applying biochar can reduce GHG emissions by 50 tons per hectare per year globally.

GHG emissions in agrifood systems encompass CO2 and non-CO2 gases, such as N2O and CH4. Several studies have delved into the impact of CSA adoption on these emissions, considering both CO2 and other components. For example, Chitakira and Ngcobo (2021) demonstrated that composting could reduce 1,026 million tons in CO2 emissions, while row seedling might decrease 887 million tons in CO2 emissions in South Africa. Jamil et al. (2023) indicated that planting late blight and cold-tolerant GM potatoes could reduce CO2 emissions by 740 million pounds, and zero tillage practices could reduce 94,000 tons in CO2 emissions. Some studies have found that CSA adoption contributes to carbon emission reduction by carbon sequestration (Kumar and Nath 2019; Sikka et al. 2018). For example, Sikka et al. (2018) found that adopting participatory integrated watershed management increases carbon sequestration in India. In addition, Iqbal et al. (2023) found that combining biochar, fertilizer, and soils of medium texture could reduce N2O emissions by 18% and CH4 emissions by 25%.

Some studies in this field focus on specific countries. For example, Taneja et al. (2014) explored the relationship between CSA adoption and GHG emissions in India. Kakraliya et al. (2021) also analyzed the impact of CSA adoption on GHG mitigation in India. They consistently found that CSA adoption reduces GHG emissions in India. Meanwhile, many studies have taken a broader perspective, examining transnational, regional, and global scales. For example, Ogle et al. (2014) revealed that adopting CSA practices contributes to reducing GHG emissions in both developing countries (Malawi, Costa Rica, Mexico, Kenya) and developed countries (the United States). Alemaw and Simalenga (2015) and Abegunde et al. (2019) concentrated on the role of CSA adoption in influencing GHG emissions in Africa. They consistently showed that CSA adoption reduces GHG emissions in Africa. Numerous pieces of literature have investigated the impact of CSA adoption on global GHG emissions (e.g., Acosta-Alba et al. 2019; Ariani et al. 2018; Jamil et al. 2023). This broad scope reflects that GHG emissions are not confined to regional boundaries and require global responses.

In summary, increasing CSA adoption does contribute to lowering GHG emissions. However, pinpointing a specific CSA group for GHG reduction is challenging. The influence and magnitude of CSA adoption are context-specific, influenced by factors such as study location, period, and types of GHGs.

5.2 Impacts on soil quality

Given the significant contribution of GHG emissions from cropland and soil to the overall emissions, it becomes crucial to focus on carbon sequestration in soils and biomass, reducing soil erosion and preventing soil fertility decline. Our review examined seven papers investigating how CSA adoption impacts soil conditions (see Table 7). These indicators encompass soil organic matter and soil fertility (Shrestha et al. 2014; Mujeyi and Mudhara 2021), soil moisture (Komarek et al. 2019), soil carbon stock (Tadesse et al. 2021), and soil nutrient (Recha et al. 2022).

The literature findings in this realm consistently affirm that CSA adoption enhances soil quality. This is achieved through augmenting organic matter content, enhancing porosity, and improving nutrient levels. For example, Hamidov et al. (2018) studied CSA adoption across 13 European countries and demonstrated that it positively influences soil functions and organic carbon storage. Komarek et al. (2019) observed that integrated soil fertility management adoption in Ethiopia enhances soil fertility, moisture, and conservation while reducing soil erosion. Recha et al. (2022), in their analysis of multiple CSA adoptions in Uganda, Kenya, and Tanzania, found that it leads to improvements in both soil macronutrient and micronutrient content.

Table 6 Overview of literature analyzing the impact of CSA adoption on greenhouse gas emissions

References	Country/Region	CSA	Findings
Taneja et al. (2014)	India	Laser land leveling, crop insurance, weather advisory services, direct seeding, zero tillage, irrigation scheduling, crop insurance	GHG emission (–)
Ogle et al. (2014)	Malawi, Costa Rica, Mexico, Kenya, the United States)	Agroforestry, agronomy, improved feeding practice, grazing intensity	GHG emissions: Malawi maize intercropping (-3.5–4.1%) Costa Rican coffee (-10.8%) US cover crops (-1.46%) Mexico conservation planting (-7.6%) Kenya improved pasture cow diets (-0.03–1.4%) United States moderate grazing (-0.2%)
Alemaw and Simalenga (2015)	Sub-Saharan Africa	Improving soil water productivity, improved water harvesting	GHG emission (–)
Ariani et al. (2018)	World	Leaf color chart to apply *N* fertilizer, paddy soil test kit for determining basic fertilizer, organic matter amendment, intermittent irrigation	Global warming potential GHG value (-7–23%) Economic benefits (+42–129%) Yield (+0.7–1.9 tons per hectare of land)
Kumari et al. (2019)	World	Multipurpose crops, woody perrenials, cover crops, effective crop rotations, minimum tillage, crop residue management	Methane/carbon dioxide emission (–) Organic carbon (+) GHG emissions (–)
Bai et al. (2019)	World	Cover crops, conservation tillage, increasing SOC (soil organic carbon) content	SOC adoption-GHG emissions (–) Biochar applications-SOC content (+39%) Cover crops-SOC content (+6%) Conservation tillage-SOC content (+6%)
Acosta-Alba et al. (2019)	World	Compost, large quantities of imported cereals (modifying the feeding of animals)	GHG emission (–)
Abegunde et al. (2019)	sub-Saharan Africa	Sustainable intensification, carbon sequestration capacity of agriculture	GHG emission (–)
McNunn et al. (2020)	The United States	Crop rotations, tillage practices, stover removal practices, cover crop practice, nitrogen timing	GHG emission (–)

Table 6 (continued)

References	Country/Region	CSA	Findings
Israel et al. (2020)	Ghana	Soil conservation practices (Creation of swales, compost application, making contours, bush burning control, ploughing crop residues into soil) Livelihood diversification (Commercial livestock production, soya cultivation, soya processing, dry season gardening, beekeeping) Irrigation and water harvesting (water harvesting, manual pump irrigation)	GHG emission (–)
Aryal et al. (2020)	South Asia	Tillage and residue management and residue management, water management, agroforestry, alternate wetting and drying, site-specific nutrient management, baira farming system, crop diversification to less water-intensive crop such as maize, improved livestock management	GHG emission (–)
Kakraliya et al. (2021)	India	Conventional tillage, reduced tillage, recommended dose of fertilizer, zero tillage, green seeker + tensiometer, nutrient-expert tool	Lower GWP under CSAPs- emission (-36–44%)
Chitakira and Ngcobo (2021)	South Africa	Conventional, tractor ploughing planting basins, zero tillage, hand digging, crop rotation, sole cropping, intercrop, mulching/cover crop, inorganic, organic, leaf litter, animal manure, no fertilizer, manual irrigation, drip irrigation, surface irrigation, sprinklers	Composting-CO2 emissions (-1,026 million tons) Row seeding-CO2 emissions (-887 million tons)
Teklu et al. (2022)	Ethiopia	Soil and water conservation, improved variety, rotation, compost, row planting, agroforestry	GHG emission (–)
Anuga et al. (2022)	Ghana	Organic fertilizer input, residue incorporation, no-inorganic fertilizer, no-pesticide input	GHG emission intensity: Sorghum (-93.2 ± 25 kg CO2e GHG kg) Rice (-79.2 ± 22 kg CO2e GHG kg) Groundnut (-69.7 ± 20 kg CO2e GHG kg)
Zhao et al. (2023)	World	New CSA practice, “Internet + weather” service	GHG emission (–)

Table 6 (continued)

References	Country/Region	CSA	Findings
Jamil et al. (2023)	World	Practices (agroforestry, crop rotation, crop diversification, laser levelling) that can enhance enhancing soil organic matter, water holding, retention capacity of soil	Planting late blight and cold tolerant GM potato yields- CO2 emissions (-740 million pounds) Zero tillage- CO2 emissions (94,000 tons)
Iqbal et al. (2023)	World	Regenerative practices adoption, biochar applying,	Biochar-GHG emissions (-50 tons per hectare per year), Biochar alone-global warming potential (-144%), Combined biochar and fertilizer, soils of medium texture-N2O (-18%) and CH4 (-25%) emissions
Brouziyne et al. (2023)	World	Improving soil quality, managing enteric fermentation	No-till systems-soil organic carbon (SOC) (+13.6%) Fallow-wheat-grass sequestered-SOC (+11.7%)

Negative impact (-)

6 Conclusions and policy implications

6.1 Conclusions

This study aims to comprehensively understand how adopting CSA affects farm productivity and incomes, resilience, and greenhouse gas emissions. Our thorough review includes examining 107 scholarly papers. We have categorized the existing literature into three categories corresponding to the three CSA goals. This categorization of the literature based on CSA objectives serves as an analytical framework, enabling the identification of effective strategies and approaches tailored to specific CSA goals.

The study's results offer valuable insights into the impact of CSA adoption. Regarding the first CSA goal to sustainably increase agricultural productivity and incomes, our analysis reveals that CSA adoption enhances farm productivity and incomes through increased crop yields and productivity, income, and technical and resource use efficiency. Addressing the second CSA goal of fostering resilience in people and agrifood systems against climate change, our findings demonstrate that CSA adoption bolsters individuals' resilience by boosting food consumption, dietary diversity, and food security. Moreover, at the system level, CSA adoption enhances agrifood system resilience by mitigating production risks and decreasing vulnerability. Concerning the third CSA goal of lowering GHG emissions, our review establishes that CSA adoption contributes to reducing emissions, including CO2, N2O, and CH4. In addition, CSA adoption promotes carbon sequestration in soils and biomass, thereby improving soil quality.

6.2 Policy implications

Drawing definitive policy implications about the overall effectiveness of CSA adoption requires careful consideration. Firstly, our review highlights that the positive impact of CSA adoption on these goals is context-dependent. Acknowledging this context specificity, policymakers are urged to adopt an approach that tailors CSA strategies to each region's unique socio-economic, environmental, and geographic conditions. In addition, it is imperative to recognize that no one-size-fits-all CSA strategy guarantees universal success. Policymakers should prioritize flexibility in policy frameworks, allowing for adaptation to the distinct characteristics of various agricultural landscapes. This flexibility will enable the effective customization of CSA practices, ensuring their alignment with the specific challenges and opportunities faced by farmers in diverse regions.

Secondly, it is essential to note that the published literature does not always yield consistent findings regarding the positive effects of CSA adoption. In some instances, we observe cases where CSA adoption has not proven to be effective. In addition, the tendency to publish studies with positive results while neglecting those with negative or inconclusive outcomes can introduce a bias in the overall literature. This selective reporting can skew our understanding of a particular phenomenon and lead to an incomplete or distorted view of the research landscape. Policymakers must be aware of this potential bias. Encouraging researchers to disseminate comprehensive findings, regardless of the direction of outcomes, is essential for mitigating the risk of skewed perspectives in formulating evidence-based policies.

Table 7 Overview of literature analyzing the impact of CSA adoption on soil quality

References	Country	CSA	Outcomes and influence
Shrestha et al. (2014)	Nepal	Improving fym quality and retaining fertilizer value of cattle urine, composting and crop residue management, integrated plant nutrient management system, preparation and use of botanical pesticides for managing crop pests, mulching/cover crops, water management strategies, inclusion of legumes into cropping system, growing drought tolerant crops/cultivars, system of rice intensification, fodder and forage crops,	Soil organic matter (+) Soil fertility and structure (+) Workability (+) Moisture characteristics (+)
Hamidov et al. (2018)	13 European countries	Crops and crop rotation, increase conservation tillage, minimize tillage traffic, small increase in irrigation extent, increase irrigation for key crops, control drainage, improve drainage system, increase/ reduce fertilization, increase cropland, reduce grassland, reduced area in rotation, increase cropland	Soil functions of food and biomass production (+) Soil organic carbon storage, and storing filtering, transforming, and recycling capacities (+)
Komarek et al. (2019)	Ethiopia	Integrated soil fertility management	Soil fertility (+) Soil erosion (–) Soil moisture (+) Soil and water conservation (+)
Bai et al. (2019)	Not specified	Conservation tillage, cover crop, biochar	Soil texture (+) Soil depth (+) Soil pH (+)
Tadesse et al. (2021)	Ethiopia	Soil and water conservation structures combined with biological measures, hedgerow planting, crop residue management, grazing management, crop rotation, and perennial crop-based agroforestry systems	Soil fertility (+) Soil carbon stock (+) Moisture content (+)
Mujeyi et al. (2021)	Zimbabwe	Minimum tillage, mulching, intercropping, rotation, manure use, drought-tolerant maize, orange maize, and improved legumes	Soil fertility in fields (+)
Recha et al. (2022)	Uganda, Kenya, and Tanzania	Use of farmyard manure, addition of ash and household waste, integration of leguminous trees, fruit trees, crops, and vegetables, integrated physical and biological soil and water conservation measures, crop rotation, improved varieties, intercropping, area enclosure, cut-and-carry system, rotational grazing, integrated physical and biological, soil and water conservation measures	Soil macronutrient (+) Soil micronutrient (+)

Positive and statistically significant impact (+); Negative and statistically significant impact (-); No statistically significant impact (NS)

Appendix

Table 8 Overview of literature analyzing the impact of CSA adoption on crop yields and productivity

References	Country	CSA	Outcomes and influence
Xiong et al. (2014)	China	Agricultural intensification together, increased application of chemical fertilizer, improved crop varieties and management	Rice yield (+)
Arslan et al. (2015)	Zambia	Minimum soil disturbance, crop rotation, legume intercropping, inorganic fertilizer, improved seed	Maize yield (+)
Fao (2015)	Zambia	Minimum soil disturbance, crop rotation, legume intercropping	Maize yield (+)
Abid et al. (2016)	Pakistan	Changing planting dates, crop varieties, fertilizer types	Wheat yields (+) Wheat productivity (+)
Khatri-Chhetri et al. (2016)	India	Improve crop varieties, crop diversification, laser land levelling, zero tillage practice	Yield (+) (rice and wheat)
Kimaro et al. (2016)	Tanzania	Reduced tillage, mulch, leguminous cover crop, leguminous trees, nitrogen fertilizer	Maize yield (+)
Thierfelder et al. (2016)	Mozambique	Minimum soil disturbance, crop residue retention, crop rotations	Maize yield (+) Legumes yield (+)
Arslan et al. (2017)	Tanzania	Maize-legume intercropping, soil and water conservation practices, organic fertilizers, inorganic fertilizers, high yielding maize varieties	Maize productivity (+) Maize yield (+)
Ariani et al. (2018)	Java	Leaf color chart to apply *N* fertilizer, paddy soil test kit for determining basic fertilizer, organic matter amendment, intermittent irrigation	Rice yield (+)
Brouziyne et al. (2018)	Morocco	No tillage, early sowing	Water yield (+)
Gorst et al. (2018)	Pakistan	Alterations in crop timing, crop switching, agricultural inputs, soil or water conservation technologies	Rice productivity (+) Wheat productivity (NS)
Khanal et al. (2018c)	Nepal	Grow drought tolerant varieties, grow short duration varieties, grow disease/pest resistant varieties, grow flood tolerant varieties, change planting location of varieties, increase seed rate, cultivation of direct seeded rice, change sowing/planting/harvesting date, seed priming, improve/increase irrigation, construction of water ways during heavy rainfall, reduce tillage, increasing number of weeding, soil conservation techniques, improve/increase chemical fertilizer use, improve/increase farm yard manure use, use more pesticides	Rice yields (+)
Sun et al. (2018)	China	Genetic improvements, agronomic management	Wheat yields (+)
Ghosh (2019)	India	Improved seeds, laser land levelling, zero tillage	Wheat yield (+)
Makate et al. (2019)	Malawi and Zimbabwe	Conservation agriculture, improved legume, drought tolerant maize	Cereal and legume productivity (+)
Midingoyi et al. (2019)	Kenya	Fruit fly integrated pest management	Mango yield (+)

Table 8 (continued)

References	Country	CSA	Outcomes and influence
Zhao et al. (2019)	China	Forage reserve, livestock breeding improvement, go out for work, cooperation round rotation, reduce livestock, grazing into homes feeding, site walks	Grass yield (+) Livestock number (+)
Amadu et al. (2020)	Malawi	Agroforestry, apiculture, check dams, continuous contour trenches, stone bunds, marker ridges, vetiver grass, water absorption trenches	Maize yield (+)
Bairagi et al. (2020)	Cambodian	Drought/flood-resistant rice varieties, integrated pest management practices, weather advisory	Rice productivity (+) Rice yield (+)
Martey et al. (2020)	Ghana	Drought-tolerant maize seed, row planting	Maize yields (+)
Branca et al. (2021)	Malawi and Zambia	Tillage, minimum soil disturbance, agronomy, residue retention, agroforestry/improved fallow, soil and water conservation	Maize yield (+)
Jamil et al. (2021)	Pakistan	Irrigation, soil and crop management practices	Cotton yield (+)
Ng'ang'a et al. (2021)	India	Minimum tillage supplemental, supplemental feeding, crop rotation, improved livestock housing, improved varieties, mixed cropping, integrated nutrient management	Yield per unit area (+)
Scognamillo and Sitko (2021)	Malawi	Legume intercropping, organic fertilization, oil and water conservation structures	Maize yields (+)
Do and Ho (2022)	Vietnam	Upgrading pond dikes, lining ponds with plastic sheets, having settling ponds	Shrimp yield (+) productivity in shrimp farming (+)
Khan et al. (2022)	Pakistan	Drill the deep well, afforestation, change seeding or harvesting date, buy climate insurance, change crop varieties, boost fertilizer and pesticides usage, rise irrigation frequency and amount	Maize productivity (+)
Wang et al. (2022)	India and Bangladesh	Adjusting crop calendars	Annual caloric yield (+)
Zizinga et al. (2022)	Uganda	Half-moon, mulching, permanent planting basins	Grain yield (+)
Dey et al. (2023)	India	Crop insurance, system of rice intensification, drought-tolerant varieties	Paddy yield (+)
Kien et al. (2023)	Vietnam	Canal irrigation, agricultural conservation practices	Rice yield (+)
Muneer et al. (2023)	Pakistan	Altering timing of cropping activity, shifting cropping patterns, altering agriculture inputs, soil conservation, water conservation, income diversification, infrastructure development	Wheat yield (+) Rice yield (+) Wheat productivity (+)

Positive and statistically significant impact (+); Negative and statistically significant impact (–); No statistically significant impact (NS)

Table 9 Overview of literature analyzing the impact of CSA adoption on income-related indicators

References	Country	CSA	Outcomes and influence
Abid et al. (2016)	Pakistan	Changing planting dates, crop varieties, fertilizer types, and planting trees	Crop income (+) (wheat)
Khatri-Chhetri et al. (2016)	India	Improve crop varieties, crop diversification, laser land levelling, zero tillage practice	Income (+) (rice and wheat)
Brüssow et al. (2017)	Tanzania	Adjustments to farm and crop management, diversification of income sources beyond the farm, soil and water conservation strategies, and planting trees or shrubs in agricultural crop and livestock production systems	Household's net income (+)
Teklewold et al. (2017)	Ethiopia	Agricultural water management, improved crop seeds, and fertilizer	Net farm income (+)
Sain et al. (2017)	Guatemala	Agroforestry systems with hedgerows, conservation tillage with mulch, contour ditches, crop rotation (maize/bean), heat and water stress-tolerant maize variety, pest- and disease-tolerant bean variety, stone barriers, water reservoirs/ponds + drip irrigation	Internal rate of return (+)
Kakraliya et al. (2018)	India	Crop residue management, nutrient management, nutrient management, ICTs, crop insurance	Profitability (+)
Song et al. (2018)	China	Irrigation, drainage	Crop net profit (NS) (Grain)
Imran et al. (2018)	Pakistan	Raising crops on bed, laser land levelling, conjunctive use of water and drainage management, minimum tillage, less use of chemicals, crop rotation and improved varieties	Gross value of cotton product (+)
Danso-Abbeam and Baiyegunhi (2018)	Ghana	Pesticides combination (Fungicides and Insecticides)	Cocoa farm income (+) Productive farm assets (+)
Fentie and Beyene (2019)	Ethiopia	Row planting	Crop income per hectare (+) (teff)
Makate et al. (2019)	Malawi, Zimbabwe	Conservation agriculture, improved legume, drought tolerant maize	Farm and household income (+)
Midingoyi et al. (2019)	Kenya	Fruit fly integrated pest management	Mango net income (+)

Table 9 (continued)

References	Country	CSA	Outcomes and influence
Mutenje et al. (2019)	Malawi, Mozambique, and Zambia	Improved maize varieties, pigeon pea intercrop, basin conservation agriculture, drought-tolerant maize, dibble-stick conservation agriculture, ground nuts rotation, ground nuts rotation, soybean rotation, relay common beans, pigeon pea intercrop, cowpea intercrop, rip line conservation agriculture,	Internal Rate of Return (+) Positive Net Present Value (IRR greater than the discount rate)
Zhao et al. (2019)	China	Forage reserve, livestock breeding improvement, go out for work, cooperation round rotation, reduce livestock, grazing into homes feeding, site walks	Herder's household income (+)
Ghosh (2019)	India	Improved seeds, laser land levelling, zero tillage	Net Return (+)
Ogada et al. (2020)	Kenya	Crop, livestock, integrated soil and water conservation, and agroforestry	Household income (+) (multiple stress-tolerant crops) Household income (–) (improved livestock breeds) Asset index [HHI index] (+)
Ojo and Baiyegunhi (2020)	Nigeria	Varying land size, sales of crops, soil and water conservation techniques, mulching, the rearing of improved varieties of livestock, mixed cropping, mono-cropping, and the use of agrochemicals	Net farm income (+)
Bairagi et al. (2020)	Cambodian	Drought/flood-resistant rice varieties, integrated pest management practices, weather advisory	Rice profit (+)
Onyeneke et al. (2020)	Nigeria	Seeking early warning information about climate risks, siting ponds far from flood-prone areas, improved fish breeds, insurance, fish diversification, livelihood diversification, sinking boreholes for regular water supply, planting shallow-rooted trees, consistently monitoring and changing pond water	Net return (+) Fish farm profit (+)
Jamil et al. (2021)	Pakistan	Irrigation, soil, and crop management practices	Net crop income (+) (cotton)
Scognamillo and Sitko (2021)	Malawi	Legume intercropping, organic fertilization, oil and water conservation structures	HH Gross Income from all crops (+)
Chiputwa et al. (2022)	Senegal	Weather and climate information services	Household income (+)

Table 9 (continued)

References	Country	CSA	Outcomes and influence
Quddoos et al. (2022)	Austria	Effective measures and high emission	Profits of farms (–)
Agarwal et al. (2022)	India	Laser land leveler, green seeker, multi-crop planter, harvester and thresher, zero tillage, leaf color chart, nutrient expert tool, relay planter and bed planter	Income index (+) (Male > female)
Belay et al. (2023)	Ethiopia	Soil and water conservation with biological measures, crop rotation (cereal/potato), improved crop varieties (high yielding beans, potato wheat), agroforestry systems (wood perennials crops), improved breeds (small ruminants), and residue incorporation (wheat/barely)	HH crop income log (+)
Dey et al. (2023)	India	Crop insurance, system of rice intensification, drought-tolerant varieties	Net income from paddy cultivation (+)
Kien et al. (2023)	Vietnam	Canal irrigation, agricultural conservation practices	Rice revenue (+) Net household income (+)

Positive and statistically significant impact (+); Negative and statistically significant impact (–); No statistically significant impact (NS)

Table 10 Overview of literature analyzing the impact of CSA adoption on food consumption, diversity, and security

References	Country	CSA	Outcomes and influence
Arslan et al. (2016)	Zambia	Diversification	Food security (+)
Douxchamps et al. (2016)	Africa	Crop diversity, soil and water conservation, trees on farm, small ruminants, improved crop varieties, fertilizers	Food security (+)
Marchant (2017)	Kenya	Crop management, field management, arm risk reduction, specific soil management practices	Food security (+)
Brüssow et al. (2017)	Tanzania	Adjustments to farm and crop management, diversification of income sources beyond the farm, soil and water conservation strategies, and planting trees or shrubs in agricultural crop and livestock production systems	Food consumption score (+) Food Security (+)
Danso-Abbeam and Baiyegunhi (2018)	Ghana	Insecticide, Fungicide, chemical fertiliser, improved seeds	Household dietary diversity score (+) Subjective food security (+)
Hasan et al. (2018)	Bangladesh	Saline-tolerant crop varieties, flood-tolerant crop varieties, drought-resistant crop varieties, early maturing rice, vegetables in a floating bed, 'sorjan' method of farming, pond-side vegetable cultivation, the cultivation of watermelon, sunflower or plum, relay cropping, urea deep placement, organic fertilizer, mulching, use of pheromone trap, rainwater harvesting and seed storage in plastic bags or glass bottles	Household food insecurity access Score (NS) Household dietary diversity score (NS) Per capita annual food expenditure (+)
Lopez-Ridaura et al. (2018)	India	Conservation agriculture and improved livestock husbandry	Household potential food availability (+)
Cholo et al. (2019)	Ethiopia	Sustainable land management, land fragmentation	Food security (+) Household dietary diversity score (+)
Midingoyi et al. (2019)	Kenya	Fruit fly integrated pest management	Human health (+) Environment (+)
Fentie and Beyene (2019)	Ethiopia	Row planting	Food security (+)
Teklewold et al. (2019)	Ethiopia	Crop diversification, soil and water conservation, and modern inputs (such as improved crop seeds and inorganic fertilizer)	Dietary diversity (+) Improves calorie and protein availability (+)
Dadzie et al. (2020)	Ghana	Changing plant variety, land rotation, use of mulching and the use of crop diversification	Household food security score (+)

Table 10 (continued)

References	Country	CSA	Outcomes and influence
Issahaku and Abdulai (2020a)	Ghana	Conservation tillage (minimum or zero-tillage), use of improved and drought-tolerant varieties, crop rotation, mixed-cropping	Household dietary diversity score (+) Household food insecurity access score (–)
Martey et al. (2020)	Ghana	Drought-tolerant maize seed, row planting	Own consumption (–) (Maize)
Oyawole et al. (2020)	Nigeria	Green manure, agroforestry, organic manure, refuse retention, crop rotation, zero/minimum tillage	Food security (+) (Refuse retention and Agroforestry)
Ali et al. (2022)	Ethiopia	Conservation agriculture, integrated soil fertility management, small-scale irrigation, agroforestry, crop diversification, improved livestock feed and feeding practice, improved animal husbandry, other (early warning systems and weather information's, support to alternative energy, crop and livestock insurance, post-harvest technologies)	Food consumption score (+) Dietary diversity score (+) Food insecurity experience scale (–) Multidimensional poverty index (–)
Abegunde et al. (2022)	South Africa	Use of organic manure, crop rotation, integrated crop-livestock management, integrated crop-livestock management	Household food security (+)
Egeru et al. (2022)	Uganda	Mulching, organic manure application, allowing land to fallow for natural regeneration to take place, boundary planting of wind breakers and shelter belts, irrigation, rain water harvesting technologies, contour, up-down slope cultivation, cover cropping, pasture growing, pasture growing, de-stocking, spraying with acaricide, cross-breeding-hybridization, rearing different livestock species (goats, sheep, cattle, donkeys), rotation grazing in pasture lands, intercropping/poly culture (multiple crops in an area in a given time), intercropping with leguminous crops, crop rotation, improved crop varieties	Food consumption scores (+)
Bazzana et al. (2022)	Ethiopia	Water and soil management actions, conservation practices	Four food security metrics Food availability (+) Self-sufficiency (+) Food instability (–) Food insecurity severity (–)

Table 10 (continued)

References	Country	CSA	Outcomes and influence
Agarwal et al. (2022)	India	Laser land leveler, green seeker, multi-crop planter, harvester, and thresher, zero tillage, leaf color chart, nutrient expert tool, relay planter and bed planter	Food security (+)
Belay et al. (2023)	Ethiopia	Soil and water conservation with biological measures, crop rotation (cereal/potato), improved crop varieties (high yielding beans, potato wheat), agroforestry systems (wood perennials crops), improved breeds (small ruminants), and residue incorporation (wheat/barely)	Food consumption score (+)
Dey et al. (2023)	India	Crop insurance, system of rice intensification, drought-tolerant varieties	Food security (+)

Positive and statistically significant impact (+); Negative and statistically significant impact (–); No statistically significant impact (NS)

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References

Abegunde VO, Sibanda M, Obi A (2022) Effect of climate-smart agriculture on household food security in small-scale production systems: a micro-level analysis from South Africa. Cogent Soc Sci 8. https://doi.org/10.1080/23311886.2022.2086343

Abegunde VO, Sibanda M, Obi A (2019) The dynamics of climate change adaptation in sub-Saharan Africa: a review of climate-smart agriculture among small-scale farmers. Climate 7. https://doi.org/10.3390/cli7110132

Abid M, Schneider UA, Scheffran J (2016) Adaptation to climate change and its impacts on food productivity and crop income: perspectives of farmers in rural Pakistan. J Rural Stud 47:254–266. https://doi.org/10.1016/j.jrurstud.2016.08.005

Acosta-Alba I, Chia E, Andrieu N (2019) The LCA4CSA framework: using life cycle assessment to strengthen environmental sustainability analysis of climate smart agriculture options at farm and crop system levels. Agric Syst 171:155–170. https://doi.org/10.1016/j.agsy.2019.02.001

Adonadaga MG, Ampadu B, Ampofo S, Adiali F (2022) Climate change adaptation strategies towards reducing vulnerability to drought in Northern Ghana. Eur J Environ Earth Sci 3:1–6. https://doi.org/10.24018/ejgeo.2022.3.4.294

Agarwal T, Goel PA, Gartaula H et al (2022) Gendered impacts of climate-smart agriculture on household food security and labor migration: insights from Bihar, India. Int J Clim Chang Strateg Manag 14:1–19. https://doi.org/10.1108/IJCCSM-01-2020-0004

Alemaw BF, Simalenga T (2015) Climate change impacts and adaptation in rainfed farming systems: a modeling framework for scaling-out climate smart agriculture in Sub-Saharan Africa. Am J Clim Chang 04:313–329. https://doi.org/10.4236/ajcc.2015.44025

Ali H, Menza M, Hagos F, Haileslassie A (2022) Impact of climate-smart agriculture adoption on food security and multidimensional poverty of rural farm households in the Central Rift Valley of Ethiopia. Agric Food Secur 11:62. https://doi.org/10.1186/s40066-022-00401-5

Ali H, Menza M, Hagos F, Haileslassie A (2023) Impact of climate smart agriculture on households' resilience and vulnerability: an example from Central Rift Valley, Ethiopia. Clim Resil Sustain 2:1–14. https://doi.org/10.1002/cli2.54

Amadu FO, Miller DC, McNamara PE (2020) Agroforestry as a pathway to agricultural yield impacts in climate-smart agriculture investments: evidence from southern Malawi. Ecol Econ 167:106443. https://doi.org/10.1016/j.ecolecon.2019.106443

Amale HS, Birthal PS, Negi DS (2022) Delayed monsoon, irrigation and crop yields. Agric Econ (United Kingdom):1–18. https://doi.org/10.1111/agec.12746

Anuga SW, Fosu-Mensah BY, Nukpezah D et al (2022) Climate-smart agriculture: greenhouse gas mitigation in climate-smart villages of Ghana. Environ Sustain 5:457–469. https://doi.org/10.1007/s42398-022-00243-8

Ariani M, Hervani A, Setyanto P (2018) Climate smart agriculture to increase productivity and reduce greenhouse gas emission-a preliminary study. IOP Conf Ser Earth Environ Sci 200. https://doi.org/10.1088/1755-1315/200/1/012024

Arslan A, Belotti F, Lipper L (2017) Smallholder productivity and weather shocks: adoption and impact of widely promoted agricultural practices in Tanzania. Food Policy 69:68–81. https://doi.org/10.1016/j.foodpol.2017.03.005

Arslan A, Cavatassi R, Alfani F et al (2016) Is diversification a climate-smart agriculture strategy in rural Zambia. Contributed paper accepted to the seventh international conference in agricultural statistics, organized by FAO and ISTAT (Italian National Institute of Statistics), Rome. (Forthcoming as FAO ESA working paper)

Arslan A, Cavatassi R, Alfani F et al (2018) Diversification under climate variability as part of a CSA strategy in rural Zambia. J Dev Stud 54:457–480. https://doi.org/10.1080/00220388.2017.1293813

Arslan A, Mccarthy N, Lipper L et al (2015) Climate smart agriculture? Assessing the adaptation implications in Zambia. J Agric Econ 66:753–780. https://doi.org/10.1111/1477-9552.12107

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

Bai X, Huang Y, Ren W et al (2019) Responses of soil carbon sequestration to climate-smart agriculture practices: a meta-analysis. Glob Chang Biol 25:2591–2606. https://doi.org/10.1111/gcb.14658

Bairagi S, Mishra AK, Durand-Morat A (2020) Climate risk management strategies and food security: evidence from Cambodian rice farmers. Food Policy 95:101935. https://doi.org/10.1016/j.foodpol.2020.101935

Bazzana D, Foltz J, Zhang Y (2022) Impact of climate smart agriculture on food security: an agent-based analysis. Food Policy 111:102304. https://doi.org/10.1016/j.foodpol.2022.102304

Belay A, Mirzabaev A, Recha JW (2023) Does climate - smart agriculture improve household income and food security ? Evidence from Southern Ethiopia. Environ Dev Sustain. https://doi.org/10.1007/s10668-023-03307-9

Bijarniya D, Parihar CM, Jat RK et al (2020) Portfolios of climate smart agriculture practices in smallholder rice-wheat system of eastern indo-gangetic plains—crop productivity, resource use efficiency and environmental foot prints. Agronomy 10. https://doi.org/10.3390/AGRONOMY10101561

Bostian AA, Bostian MB, Laukkanen M, Simola A (2020) Assessing the productivity consequences of agri-environmental practices when adoption is endogenous. J Product Anal 53:141–162. https://doi.org/10.1007/s11123-019-00564-7

Branca G, Arslan A, Paolantonio A et al (2021) Assessing the economic and mitigation benefits of climate-smart agriculture and its implications for political economy: a case study in Southern Africa. J Clean Prod 285:125161. https://doi.org/10.1016/j.jclepro.2020.125161

Brouziyne Y, Abouabdillah A, Hirich A et al (2018) Modeling sustainable adaptation strategies toward a climate-smart agriculture in a Mediterranean watershed under projected climate change scenarios. Agric Syst 162:154–163. https://doi.org/10.1016/j.agsy.2018.01.024

Brouziyne Y, El Bilali A, Epule Epule T et al (2023) Towards lower greenhouse gas emissions agriculture in North Africa through climate-smart agriculture: a systematic review. Climate 11:139. https://doi.org/10.3390/cli11070139

Brüssow K, Faße A, Grote U (2017) Implications of climate-smart strategy adoption by farm households for food security in Tanzania. Food Secur 9:1203–1218. https://doi.org/10.1007/s12571-017-0694-y

Carraro C (2016) Climate change: scenarios, impacts, policy, and development opportunities. Agric Econ (United Kingdom) 47:149–157. https://doi.org/10.1111/agec.12306

Çetin O, Kara A (2019) Assessment of water productivity using different drip irrigation systems for cotton. Agric Water Manag 223:105693. https://doi.org/10.1016/j.agwat.2019.105693

Challinor AJ, Watson J, Lobell DB et al (2014) A meta-analysis of crop yield under climate change and adaptation. Nat Clim Chang 4:287–291. https://doi.org/10.1038/nclimate2153

Chavula P (2021) A review between climate smart agriculture technology objectives' synergies and trade-offs. Int J Food Sci Agric 5:748–753. https://doi.org/10.26855/ijfsa.2021.12.023

Chiputwa B, Blundo-Canto G, Steward P et al (2022) Co-production, uptake of weather and climate services, and welfare impacts on farmers in Senegal: a panel data approach. Agric Syst 195:103309. https://doi.org/10.1016/j.agsy.2021.103309

Chitakira M, Ngcobo NZP (2021) Uptake of climate smart agriculture in Peri-Urban areas of South Africa's economic hub requires up-scaling. Front Sustain Food Syst 5:1–13. https://doi.org/10.3389/fsufs.2021.706738

Cholo TC, Fleskens L, Sietz D, Peerlings J (2019) Land fragmentation, climate change adaptation, and food security in the Gamo Highlands of Ethiopia. Agric Econ (United Kingdom) 50:39–49. https://doi.org/10.1111/agec.12464

Dadzie SKN, Inkoom EW, Akaba S et al (2020) Sustainability responses to climate-smart adaptation in Africa: implication for food security among farm households in the Central Region of Ghana. Afr J Econ Manag Stud 12:208–227. https://doi.org/10.1108/AJEMS-04-2019-0155

Danso-Abbeam G, Baiyegunhi LJS (2018) Welfare impact of pesticides management practices among smallholder cocoa farmers in Ghana. Technol Soc 54:10–19. https://doi.org/10.1016/j.techsoc.2018.01.011

Dey S, Singh PK, Abbhishek K et al (2023) Climate-resilient agricultural ploys can improve livelihood and food security in Eastern India. Environ Dev Sustain. https://doi.org/10.1007/s10668-023-03176-2

Di Falco S, Veronesi M (2014) Managing environmental risk in presence of climate change: the role of adaptation in the Nile Basin of Ethiopia. Environ Resour Econ 57:553–577. https://doi.org/10.1007/s10640-013-9696-1

Dinesh D, Frid-Nielsen S, Norman J et al (2015) Is climate-smart agriculture effective? A review of selected cases. CCAFS Working Paper

Do H-L, Ho TQ (2022) Climate change adaptation strategies and shrimp aquaculture: empirical evidence from the Mekong Delta of Vietnam. Ecol Econ 196:107411. https://doi.org/10.1016/j.ecolecon.2022.107411

Douxchamps S, Van Wijk MT, Silvestri S et al (2016) Linking agricultural adaptation strategies, food security and vulnerability: evidence from West Africa. Reg Environ Chang 16:1305–1317. https://doi.org/10.1007/s10113-015-0838-6

Egeru A, Bbosa MM, Siya A et al (2022) Micro-level analysis of climate-smart agriculture adoption and effect on household food security in semi-arid Nakasongola District in Uganda. Environ Res Clim 1:025003. https://doi.org/10.1088/2752-5295/ac875d

Fao (2015) Food security and adaptation impacts of potential climate smart agricultural practices in Zambia food and agriculture organization of the United Nations Rome, 2015. 1–29

FAO (2021) Climate-smart agriculture case studies 2021

FAO (2020) Special report: special report on climate change and land chapter 5

Fentie A, Beyene AD (2019) Climate-smart agricultural practices and welfare of rural smallholders in Ethiopia: does planting method matter? Land Use Policy 85:387–396. https://doi.org/10.1016/j.landusepol.2019.04.020

Ghosh M (2019) Climate-smart agriculture, productivity and food security in India. J Dev Policy Pract 4:166–187. https://doi.org/10.1177/2455133319862404

Gorst A, Dehlavi A, Groom B (2018) Crop productivity and adaptation to climate change in Pakistan. Environ Dev Econ 23:679–701. https://doi.org/10.1017/S1355770X18000232

Hamidov A, Helming K, Bellocchi G et al (2018) Impacts of climate change adaptation options on soil functions: a review of European case-studies. L Degrad Dev 29:2378–2389. https://doi.org/10.1002/ldr.3006

Hasan MK, Desiere S, D’Haese M, Kumar L (2018) Impact of climate-smart agriculture adoption on the food security of coastal farmers in Bangladesh. Food Secur 10:1073–1088. https://doi.org/10.1007/s12571-018-0824-1

Herrman H, Stewart DE, Diaz-Granados N et al (2011) What is resilience? Can J Psychiatry 56:258–265. https://doi.org/10.1177/070674371105600504

Ho TT, Shimada K (2019) The effects of climate smart agriculture and climate change adaptation on the technical efficiency of rice farming—an empirical study in the mekong delta of Vietnam. Agric 9. https://doi.org/10.3390/agriculture9050099

Huang J, Wang J, Wang Y (2015) Farmers’ adaptation to extreme weather events through farm management and its impacts on the mean and risk of rice yield in China. Am J Agric Econ 97:602–617. https://doi.org/10.1093/ajae/aav005

Imran MA, Ali A, Ashfaq M et al (2018) Impact of Climate Smart Agriculture (CSA) practices on cotton production and livelihood of farmers in Punjab, Pakistan. Sustain 10. https://doi.org/10.3390/su10062101

Imran MA, Ali A, Ashfaq M et al (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

IPCC (2023) AR6 synthesis report: climate change 2023

Iqbal S, Xu J, Khan S et al (2023) Regenerative fertilization strategies for climate-smart agriculture: consequences for greenhouse gas emissions from global drylands. J Clean Prod 398:136650. https://doi.org/10.1016/j.jclepro.2023.136650

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

Issahaku G, Abdulai A (2020a) Can farm households improve food and nutrition security through adoption of climate-smart practices? Empirical evidence from Northern Ghana. Appl Econ Perspect Policy 42:559–579. https://doi.org/10.1093/aepp/ppz002

Issahaku G, Abdulai A (2020b) Adoption of climate-smart practices and its impact on farm performance and risk exposure among smallholder farmers in Ghana. Aust J Agric Resour Econ 64:396–420. https://doi.org/10.1111/1467-8489.12357

Jagustović R, Papachristos G, Zougmoré RB et al (2021) Better before worse trajectories in food systems? An investigation of synergieacs and trade-offs through climate-smart agriculture and system dynamics. Agric Syst 190. https://doi.org/10.1016/j.agsy.2021.103131

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

Jamil S, Kanwal S, Kanwal R et al (2023) Climate-smart agriculture: a way to ensure food security. Pakistan J Bot 55:1157–1167. https://doi.org/10.30848/PJB2023-3(26)

Kaczan D, Arslan A, Lipper L (2013) Climate-smart agriculture ? A review of current practice of agroforestry and conservation agriculture in Malawi and Zambia ESA Working Paper No . 13–07 October 2013. FAO, Rome, Italy

Kakraliya SK, Jat HS, Sapkota TB 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. Agric 11. https://doi.org/10.3390/agriculture11121269

Kakraliya SK, Jat HS, Singh I et al (2018) Performance of portfolios of climate smart agriculture practices in a rice-wheat system of western Indo-Gangetic plains. Agric Water Manag 202:122–133. https://doi.org/10.1016/j.agwat.2018.02.020

Kakraliya SK, Jat HS, Singh I et al (2022) Energy and economic efficiency of climate-smart agriculture practices in a rice–wheat cropping system of India. Sci Rep 12:1–14. https://doi.org/10.1038/s41598-022-12686-4

Khan N, Ma J, Kassem HS et al (2022) Rural farmers' cognition and climate change adaptation impact on cash crop productivity: evidence from a recent study. Int J Environ Res Public Health 19:6–9. https://doi.org/10.3390/ijerph191912556

Khanal U, Wilson C, Hoang VN, Lee B (2018a) farmers' adaptation to climate change, its determinants and impacts on rice yield in Nepal. Ecol Econ 144:139–147. https://doi.org/10.1016/j.ecolecon.2017.08.006

Khanal U, Wilson C, Lee B, Hoang VN (2018b) Do climate change adaptation practices improve technical efficiency of smallholder farmers? Evidence from Nepal. Clim Chang 147:507–521. https://doi.org/10.1007/s10584-018-2168-4

Khanal U, Wilson C, Lee BL, Hoang VN (2018c) Climate change adaptation strategies and food productivity in Nepal: a counterfactual analysis. Clim Chang 148:575–590. https://doi.org/10.1007/s10584-018-2214-2

Khatri-Chhetri A, Aggarwal PK, Joshi PK, Vyas S (2017) Farmers' prioritization of climate-smart agriculture (CSA) technologies. Agric Syst 151:184–191. https://doi.org/10.1016/j.agsy.2016.10.005

Khatri-Chhetri A, Aryal JP, Sapkota TB, Khurana R (2016) Economic benefits of climate-smart agricultural practices to smallholder farmers in the Indo-Gangetic Plains of India. Curr Sci 110:1251–1256. https://doi.org/10.18520/cs/v110/i7/1251-1256

Kien ND, Dung TQ, Oanh DTK et al (2023) Climate-resilient practices and welfare impacts on rice-cultivating households in Vietnam: does joint adoption of multiple practices matter? Aust J Agric Resour Econ 67:263–284. https://doi.org/10.1111/1467-8489.12506

Kimaro AA, Mpanda M, Rioux J et al (2016) Is conservation agriculture 'climate-smart' for maize farmers in the highlands of Tanzania? Nutr Cycl Agroecosyst 105:217–228. https://doi.org/10.1007/s10705-015-9711-8

Komarek AM, Thurlow J, Koo J, De Pinto A (2019) Economywide effects of climate-smart agriculture in Ethiopia. Agric Econ (United Kingdom) 50:765–778. https://doi.org/10.1111/agec.12523

Kumar N, Nath CP (2019) Impact of zero-till residue management and crop diversification with legumes on soil aggregation and carbon sequestration. Soil Tillage Res 189:158–167. https://doi.org/10.1016/j.still.2019.02.001

Kumari S, Singh TP, Prasad S (2019) Climate smart agriculture and climate change. Int J Curr Microbiol Appl Sci 8:1112–1137. https://doi.org/10.20546/ijcmas.2019.803.134

Kuwayama Y, Thompson A, Bernknopf R et al (2019) Estimating the impact of drought on agriculture using the U.S. Drought Monitor Am J Agric Econ 101:193–210. https://doi.org/10.1093/ajae/aay037

Lachaud MA, Bravo-Ureta BE, Ludena CE (2021) Economic effects of climate change on agricultural production and productivity in Latin America and the Caribbean (LAC). Agric Econ (United Kingdom):1–12. https://doi.org/10.1111/agec.12682

Lipper L, Thornton P, Campbell BM et al (2014) Climate-smart agriculture for food security. Nat Clim Chang 4:1068–1072. https://doi.org/10.1038/nclimate2437

Lopez-Ridaura S, Frelat R, van Wijk MT et al (2018) Climate smart agriculture, farm household typologies and food security: an ex-ante assessment from Eastern India. Agric Syst 159:57–68. https://doi.org/10.1016/j.agsy.2017.09.007

Ma W, Vatsa P, Zheng H, Guo Y (2022) Does online food shopping boost dietary diversity? Application of an endogenous switching model with a count outcome variable. Agric Food Econ 10:30. https://doi.org/10.1186/s40100-022-00239-2

Maggio G, Mastrorillo M, Sitko NJ (2022) Adapting to high temperatures: effect of farm practices and their adoption duration on total value of crop production in Uganda. Am J Agric Econ 104:385–403. https://doi.org/10.1111/ajae.12229

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

Marchant R (2017) Effect of climate smart agricultural practices on food security of small scale farmers in Teso North Sub-County. AgEcon Search . https://doi.org/10.22004/ag.econ.276427

Martey E, Etwire PM, Abdoulaye T (2020) Welfare impacts of climate-smart agriculture in Ghana: does row planting and drought-tolerant maize varieties matter? Land Use Policy 95:104622. https://doi.org/10.1016/j.landusepol.2020.104622

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

Midingoyi S, Kifouly G, Kassie M, Muriithi B et al (2019) Do farmers and the environment benefit from adopting integrated pest management practices? Evidence from Kenya. J Agric Econ 70:452–470. https://doi.org/10.1111/1477-9552.12306

Miller N, Tack J, Bergtold J (2021) The impacts of warming temperatures on US sorghum yields and the potential for adaptation. Am J Agric Econ 103:1742–1758. https://doi.org/10.1111/ajae.12223

Mishra A, Ketelaar JW, 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. Int J Agric Sustain 19:152–174

Moher D, Shamseer L, Clarke M et al (2015) Preferred reporting items for systematic review and meta-analysis protocols (PRISMA-P) 2015 statement. Syst Rev 4:1–9

Mujeyi A, Mudhara M (2021) Economic analysis of climate-smart agriculture technologies in maize production in smallholder farming systems. Afr Handb Clim Chang Adapt With 610 Fig 361 Tables:225–240. https://doi.org/10.1007/978-3-030-45106-6_17

Mujeyi A, Mudhara M, Mutenje M (2021) The impact of climate smart agriculture on household welfare in smallholder integrated crop–livestock farming systems: evidence from Zimbabwe. Agric Food Secur 10:1–15. https://doi.org/10.1186/s40066-020-00277-3

Muneer S, Bakhsh K, Ali R et al (2023) Farm households' perception and adaptation to climate change in relation of food crop productivity in Pakistan. Environ Dev Sustain. https://doi.org/10.1007/s10668-023-03333-7

Mutenje MJ, Farnworth CR, Stirling C et al (2019) A cost-benefit analysis of climate-smart agriculture options in Southern Africa: balancing gender and technology. Ecol Econ 163:126–137. https://doi.org/10.1016/j.ecolecon.2019.05.013

Neuenschwander P, Borgemeister C, De Groote H et al (2023) Perspective article: food security in tropical Africa through climate-smart plant health management; a new framework for sustainable plant health management. Heliyon 9:1–8. https://doi.org/10.1016/j.heliyon.2023.e15116

Ng'ang'a SK, Miller V, Girvetz E (2021) Is investment in Climate-Smart-agricultural practices the option for the future? Cost and benefit analysis evidence from Ghana. Heliyon 7:e06653. https://doi.org/10.1016/j.heliyon.2021.e06653

Ogada MJ, Rao EJO, Radeny M et al (2020) Climate-smart agriculture, household income and asset accumulation among smallholder farmers in the Nyando basin of Kenya. World Dev Perspect 18:100203. https://doi.org/10.1016/j.wdp.2020.100203

Ogle SM, Olander L, Wollenberg L et al (2014) Reducing greenhouse gas emissions and adapting agricultural management for climate change in developing countries: providing the basis for action. Glob Chang Biol 20:1–6. https://doi.org/10.1111/gcb.12361

Ogola RJO, Ouko KO (2021) Synergies and trade-offs of selected climate smart agriculture practices in Irish potato farming, Kenya. Cogent Food Agric 7. https://doi.org/10.1080/23311932.2021.1948257

Ojo TO, Baiyegunhi LJS (2020) Determinants of climate change adaptation strategies and its impact on the net farm income of rice farmers in south-west Nigeria. Land Use Policy 95:103946. https://doi.org/10.1016/j.landusepol.2019.04.007

Onyeneke RU, Igberi CO, Aligbe JO et al (2020) Climate change adaptation actions by fish farmers: evidence from the Niger Delta Region of Nigeria. Aust J Agric Resour Econ 64:347–375. https://doi.org/10.1111/1467-8489.12359

Oyawole FP, Dipeolu AO, Shittu AM et al (2020) Adoption of agricultural practices with climate smart agriculture potentials and food security among farm households in northern Nigeria. Open Agric 5:751–760. https://doi.org/10.1515/opag-2020-0071

Pangapanga-Phiri I, Mungatana ED (2021) Adoption of climate-smart agricultural practices and their influence on the technical efficiency of maize production under extreme weather events. Int J Disaster Risk Reduct 61:102322. https://doi.org/10.1016/j.ijdrr.2021.102322

Partey ST, Zougmoré RB, Ouédraogo M, Campbell BM (2018) Developing climate-smart agriculture to face climate variability in West Africa: challenges and lessons learnt. J Clean Prod 187:285–295. https://doi.org/10.1016/j.jclepro.2018.03.199

Quddoos A, Salhofer K, Morawetz UB (2022) Utilising farm-level panel data to estimate climate change impacts and adaptation potentials. J Agric Econ:1–25. https://doi.org/10.1111/1477-9552.12490

Recha JW, Ambaw G, Nigussie A et al (2022) Soil nutrient contents in East African Climate-smart villages: effects of climate-smart agriculture interventions. Agriculture 12:1–15. https://doi.org/10.3390/agriculture12040499

Ritchie H, Roser M (2020) Environmental impacts of food production. In: OurWorldInData.org

Sain G, Loboguerrero AM, Corner-Dolloff C et al (2017) Costs and benefits of climate-smart agriculture: the case of the dry corridor in Guatemala. Agric Syst 151:163–173. https://doi.org/10.1016/j.agsy.2016.05.004

Salat M, Swallow B (2018) Resource use efficiency as a climate smart approach: case of smallholder maize farmers in Nyando, Kenya. Environ - MDPI 5:1–15. https://doi.org/10.3390/environments5080093

Sarr M, Bezabih Ayele M, Kimani ME, Ruhinduka R (2021) Who benefits from climate-friendly agriculture? The marginal returns to a rainfed system of rice intensification in Tanzania. World Dev 138:105160. https://doi.org/10.1016/j.worlddev.2020.105160

Schaub S, Ghazoul J, Huber R et al (2023) The role of behavioural factors and opportunity costs in farmers' participation in voluntary agri-environmental schemes: a systematic review. J Agric Econ:1–44. https://doi.org/10.1111/1477-9552.12538

Schmitt J, Offermann F, Söder M et al (2022) Extreme weather events cause significant crop yield losses at the farm level in German agriculture. Food Policy 112:102359. https://doi.org/10.1016/J.FOODPOL.2022.102359

Scognamillo A, Sitko NJ (2021) Leveraging social protection to advance climate-smart agriculture: an empirical analysis of the impacts of Malawi's Social Action Fund (MASAF) on farmers' adoption decisions and welfare outcomes. World Dev 146:105618. https://doi.org/10.1016/j.worlddev.2021.105618

Shahzad MF, Abdulai A (2020) Adaptation to extreme weather conditions and farm performance in rural Pakistan. Agric Syst 180:102772. https://doi.org/10.1016/j.agsy.2019.102772

Shrestha A, Bishwakarma BK, Allen R (2014) Climate smart management options for improving the soil fertility and farm productivity in the middle hills of Nepal. Univers J Agric Res 2:253–263. https://doi.org/10.13189/ujar.2014.020705

Sikka AK, Islam A, Rao KV (2018) Climate-smart land and water management for sustainable agriculture. Irrig Drain 67:72–81. https://doi.org/10.1002/ird.2162

Song C, Liu R, Oxley L, Ma H (2018) The adoption and impact of engineering-type measures to address climate change: evidence from the major grain-producing areas in China. Aust J Agric Resour Econ 62:608–635. https://doi.org/10.1111/1467-8489.12269

Sun S, Yang X, Lin X et al (2018) Climate-smart management can further improve winter wheat yield in China. Agric Syst 162:10–18. https://doi.org/10.1016/j.agsy.2018.01.010

Tadesse M, Simane B, Abera W et al (2021) The effect of climate-smart agriculture on soil fertility, crop yield, and soil carbon in Southern Ethiopia. Sustainability 13:1–11. https://doi.org/10.3390/su13084515

Taneja G, Pal BD, Joshi PK et al (2014) Farmerss preferences for climate-smart agriculture: an assessment in the Indo-Gangetic Plain. SSRN Electron J. https://doi.org/10.2139/ssrn.2420547

Teklewold H, Gebrehiwot T, Bezabih M (2019) Climate smart agricultural practices and gender differentiated nutrition outcome: an empirical evidence from Ethiopia. World Dev 122:38–53. https://doi.org/10.1016/j.worlddev.2019.05.010

Teklewold H, Mekonnen A, Kohlin G, DI Falco S (2017) Does adoption of multiple climate-smart practices improve farmers' climate resilience? Empirical evidence from the Nile Basin of Ethiopia. Clim Chang Econ 8. https://doi.org/10.1142/S2010007817500014

Teklu A, Simane B, Bezabih M (2022) Effectiveness of climate-smart agriculture innovations in smallholder agriculture system in Ethiopia. Sustainability 14. https://doi.org/10.3390/su142316143

Thierfelder C, Rusinamhodzi L, Setimela P et al (2016) Conservation agriculture and drought-tolerant germplasm: reaping the benefits of climate-smart agriculture technologies in central Mozambique. Renew Agric Food Syst 31:414–428. https://doi.org/10.1017/S1742170515000332

Tilahun G, Bantider A, Yayeh D (2023) Synergies and trade-offs of climate-smart agriculture (CSA) practices selected by smallholder farmers in Geshy watershed, Southwest Ethiopia. Reg Sustain 4:129–138. https://doi.org/10.1016/j.regsus.2023.04.001

Tong Q, Swallow B, Zhang L, Zhang J (2019) The roles of risk aversion and climate-smart agriculture in climate risk management: evidence from rice production in the Jianghan Plain, China. Clim Risk Manag 26:100199. https://doi.org/10.1016/j.crm.2019.100199

Wang X, Folberth C, Skalsky R et al (2022) Crop calendar optimization for climate change adaptation in rice-based multiple cropping systems of India and Bangladesh. Agric For Meteorol 315:108830. https://doi.org/10.1016/j.agrformet.2022.108830

Wang Y, Huang J, Wang J, Findlay C (2018) Mitigating rice production risks from drought through improving irrigation infrastructure and management in China. Aust J Agric Resour Econ 62:161–176. https://doi.org/10.1111/1467-8489.12241

Wouterse F, Andrijevic M, Schaeffer M (2022) The microeconomics of adaptation: evidence from smallholders in Ethiopia and Niger. World Dev 154:105884. https://doi.org/10.1016/j.worlddev.2022.105884

Xiong W, van der Velde M, Holman IP et al (2014) Can climate-smart agriculture reverse the recent slowing of rice yield growth in China? Agric Ecosyst Environ 196:125–136. https://doi.org/10.1016/j.agee.2014.06.014

Zhao J, Liu D, Huang R (2023) A review of climate-smart agriculture: recent advancements, challenges, and future directions. Sustain 15:1–15. https://doi.org/10.3390/su15043404

Zhao Z, Wang G, Chen J et al (2019) Assessment of climate change adaptation measures on the income of herders in a pastoral region. J Clean Prod 208:728–735. https://doi.org/10.1016/j.jclepro.2018.10.088

Zheng H, Ma W (2023) Economic benefits of internet use for smallholder wheat farmers. Appl Econ 00:1–16. https://doi.org/10.1080/00036846.2023.2167928

Zheng H, Ma W, Li G (2021a) Adoption of organic soil amendments and its impact on farm performance: evidence from wheat farmers in China*. Aust J Agric Resour Econ 65:367–390. https://doi.org/10.1111/1467-8489.12406

Zheng H, Ma W, Wang F, Li G (2021b) Does internet use improve technical efficiency of banana production in China? Evidence from a selectivity-corrected analysis. Food Policy 102:102044. https://doi.org/10.1016/j.foodpol.2021.102044

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

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