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Review

The multifaceted impact of climate change on agricultural productivity: a systematic literature review of SCOPUS-indexed studies (2015–2024)

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Received: 19 January 2025 / Accepted: 28 April 2025
Published online: 13 May 2025

Abstract
This study examines the multifaceted impacts of climate change on agricultural productivity. A systematic literature review (SLR) was conducted using the SCOPUS database, following PRISMA guidelines. The study targeted peer-reviewed articles published between 2015 and 2024, leading to the selection of 77 high-quality studies. Thematic analysis was employed to categorize research into key themes, including agricultural productivity, climate adaptation, food security, and technological advancements. The review finds that climate change significantly impacts global agricultural productivity, with projections indicating up to a 14% decline in food production by 2050 if adaptation measures are not implemented. Climate-Smart Agriculture (CSA) practices enhance productivity by 10.5% and profitability by 29.4% but face barriers such as financial constraints and inadequate infrastructure. Soil and water management strategies, such as cover cropping, conservation tillage, and high-efficiency irrigation, have proven effective in improving resilience but require policy and financial support for large-scale adoption. Technological innovations, including AI-driven precision farming, satellite-based climate monitoring, and early warning systems, offer promising solutions but require integration with farmer education and policy incentives. Policy interventions such as carbon pricing, climate-resilient subsidies, and trade liberalization can mitigate climate risks and promote sustainable agricultural practices. This study emphasizes that a holistic, multi-disciplinary approach integrating technology, policy, and socioeconomic factors is critical for developing resilient agricultural systems. Policymakers, researchers, and agricultural practitioners must collaborate to bridge knowledge gaps, enhance access to adaptation resources, and implement sustainable agricultural practices. Future research should focus on long-term adaptation strategies, improved governance frameworks, and inclusive policies that prioritize vulnerable farming communities to ensure global food security amid climate uncertainties. *Clinical trial number:* Not applicable.

Keywords Climate change · Agricultural productivity · Climate smart agriculture · Food security · Technological and policy Innovations

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s43621-025-01229-2.

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1 Introduction

Agriculture, a cornerstone of global food security and economic development, faces unprecedented challenges stemming from climate change [60]. Rising temperatures, erratic rainfall, and extreme weather events have disrupted agricultural productivity, posing severe threats to food security and rural livelihoods worldwide [40].

Climate change directly impacts agricultural productivity by accelerating soil erosion, increasing pest and disease prevalence, depleting soil fertility, and intensifying drought and flood risks [33, 62, 63]. These disruptions weaken food production systems, reducing crop yields and livestock productivity, which in turn exacerbates food insecurity at both local and global levels.

Projections indicate that global food production could decline by up to 14% by 2050, with the most severe consequences expected in Sub-Saharan Africa, South Asia, and parts of Latin America [3, 7, 29]. In these regions, smallholder farmers—who form the backbone of food production—are particularly vulnerable to climate-induced stressors, including prolonged droughts, erratic rainfall, and declining soil fertility. As yields shrink and agricultural productivity declines, food shortages become more frequent, worsening malnutrition and economic instability [29, 40]. Additionally, climate-induced stressors disrupt global supply chains, destabilize trade dynamics, and hinder food distribution systems, leading to rising food prices, restricted market access, and increased financial strain on both consumers and producers [13]. These price increases disproportionately affect low-income populations, making nutritious food increasingly unaffordable and heightening hunger risks [35].

Beyond food security, climate change exacerbates socioeconomic challenges by increasing poverty, widening income inequality, and straining public health systems. It disrupts livelihoods, particularly for those dependent on agriculture and natural resources, resulting in job losses and economic instability. Additionally, rising temperatures and extreme weather events damage infrastructure, displace communities, and increase financial burdens on governments, making it harder for vulnerable populations to recover and adapt [31, 43].

To mitigate these challenges, sustainable soil and water resource management strategies have become essential for preserving land productivity, optimizing irrigation efficiency, and enhancing climate resilience [1, 54]. Soil conservation techniques—including cover cropping, crop rotation, conservation tillage, and improved irrigation practices—have demonstrated positive effects on soil health, carbon sequestration, and water retention, making them critical tools for sustainable agriculture [54]. Additionally, high-efficiency irrigation (HEI) technologies and rainwater harvesting have significantly improved crop survival rates and yield stability in drought-prone regions [23].

A growing body of research highlights Climate-Smart Agriculture (CSA) as a key adaptation strategy, integrating sustainable farming techniques, precision agriculture, and resilient crop varieties to enhance productivity under changing climatic conditions [2, 22]. Studies show that CSA adoption has led to a 10.5% increase in productivity, a 29.4% rise in profitability, and a 43% reduction in greenhouse gas emissions [9]. However, barriers such as limited financial access, inadequate infrastructure, and low farmer awareness—particularly in low-income regions—continue to hinder widespread implementation [22].

Beyond sustainable practices, technological and policy innovations play a crucial role in mitigating climate change's adverse effects on agriculture [16, 27]. Advanced technologies, such as satellite-based climate monitoring, early warning systems, and AI-driven precision farming tools, provide real-time adaptation and risk management solutions [27]. Additionally, policy interventions—including climate-resilient agricultural subsidies, carbon tax programs, and investments in climate adaptation research—are essential for fostering long-term agricultural resilience and food security [13, 47].

Given the complex and far-reaching implications of climate change on agriculture, a systematic literature review (SLR) is necessary to consolidate existing research, synthesize findings, and identify key knowledge gaps. While numerous studies have examined the effects of climate change on food production, soil health, and adaptation strategies, research remains fragmented, with varied methodologies and region-specific analyses yielding inconsistent conclusions. Some studies focus on macroeconomic impacts, such as changes in global food supply, agricultural GDP, and trade patterns, while others explore localized effects on farming systems, smallholder resilience, and technological adoption [21, 49].

Furthermore, much of the literature has concentrated on specific climate risks in select regions, often overlooking broader implications for global food security, policy frameworks, and socioeconomic transformations. As climate variability intensifies and agricultural landscapes evolve, a comprehensive review is essential to assess cumulative impacts, emerging trends, and adaptation strategies across diverse agricultural contexts.

This systematic literature review aims to critically examine and synthesize research on the multidimensional impacts of climate change on agricultural productivity. Specifically, it seeks to:

- To examine the effects of climate change on agricultural productivity and crop yields in different contexts.
- Assess soil and water resource management strategies that enhance agricultural productivity by improving soil health, optimizing water efficiency, and increasing crop yields.
- Evaluate the implications of climate change on food security.
- Examine the effectiveness of adaptation strategies, including climate-smart agriculture and conservation practices, in mitigating agricultural losses.
- Investigate the role of technology and policy innovations in enhancing agricultural resilience and promoting sustainable farming practices.
- Identify key research gaps and future directions, particularly in terms of long-term climate adaptation planning, interdisciplinary methodologies, and policy integration.

This study will employ a systematic literature review methodology to ensure a comprehensive and structured analysis of existing research. The review process will involve searching academic databases, particularly SCOPUS, to identify high-quality, peer-reviewed studies published between 2015 and 2024. To maintain rigor, studies will be selected based on relevance, methodological quality, and geographic representation. A thematic analysis approach will categorize research into key themes, including agricultural productivity, climate adaptation, food security, and technological advancements. Additionally, regional disparities, policy frameworks, and economic models will be assessed to compare variations in climate impacts and adaptation strategies across different contexts.

The findings of this systematic review will provide valuable insights for policymakers, agricultural stakeholders, researchers, and international organizations seeking to understand the long-term impact of climate change on agricultural systems. By identifying patterns and trends in existing research, this study will contribute to the ongoing discourse on climate adaptation, food security, and sustainable agricultural strategies. Additionally, it will offer policy recommendations and future research directions, particularly in areas where empirical data is limited or where interdisciplinary approaches could enhance agricultural resilience.

1.1 Paper structure

- Section 1*:* Introduction—Provides an overview of climate change, its agricultural implications, and the significance of adaptation strategies.
- Section 2*:* Methods—Outlines the systematic literature review methodology and key empirical studies on climate change and agriculture.
- Section 3*:* Thematic Analysis and Discussion—Examines key themes related to climate change and agriculture, providing critical insights and interpretations.
- Section 4*:* Conclusion, Research Limitations, Future Research Directions, and Research Implications—Summarizes key findings, highlights research limitations, suggests directions for future research, and discusses the broader implications of the study.

2 Methodology

2.1 Research design

This study employs a Systematic Literature Review (SLR) to provide a comprehensive analysis of research literature on climate change's impact on agricultural productivity. The SLR method ensures rigor, transparency, and objectivity by synthesizing existing literature in a well-organized manner. Following Snyder's (2019) framework, this review consolidates empirical findings from peer-reviewed studies to provide insights into its effects. The study adheres to PRISMA guidelines [42] to ensure methodological rigor and transparency.

2.2 Systematic review procedure

Following the methods outlined by Pickering and Byrne [48] and Moher et al. [42], this study adopted a five-step systematic review process:

- *Defining Objectives and Research Questions:* Establishing the review's purpose and key research questions.
- *Developing Search Criteria:* Identifying search terms, databases, and inclusion criteria for literature selection.
- *Conducting Searches:* Executing database queries, screening results, and refining selections based on criteria.
- *Evaluating Literature:* Assessing the quality and relevance of selected studies and summarizing their findings in tabular form.
- *Synthesizing Results:* Integrating findings and highlighting research gaps for future exploration.

2.3 Define review objectives and develop research questions

This systematic review aims to critically analyze the impact of climate change on agricultural productivity by drawing insights from Scopus-indexed publications spanning 2015–2024. The study addresses the following research questions:

1. How does climate change impact agricultural productivity and crop yields across different agro-ecological zones?
2. What are the most effective soil and water resource management strategies for enhancing agricultural productivity and resilience?
3. How effective are climate-smart agriculture (CSA) practices and conservation strategies in mitigating agricultural losses and improving farm resilience?
4. What are the implications of climate change for food security, particularly in vulnerable regions?
5. What are the key research gaps and future directions in agricultural adaptation to climate change, particularly concerning long-term adaptation planning, interdisciplinary approaches, and policy integration?

2.4 Identify search terms, inclusion criteria and databases

The SCOPUS database was selected for its extensive coverage of peer-reviewed research and access to reliable, high-quality publications, exceeding the standards of many free databases [4, 52, 64]. The search query used was: TITLE-ABS-KEY (climate change AND agricultural productivity), targeting studies specifically focusing on the relationship between climate change and agricultural productivity. The inclusion and exclusion criteria are summarized in Table 1.

2.5 Selection criteria and assessing literature quality and relevance

The study employed a systematic approach to identify research on the impact of climate change on agricultural productivity. An initial search yielded 2186 publications. Through a multi-stage refinement process:

- Publications prior to 2015 were excluded, reducing results to 1449 publications.
- Excluding non-relevant subject areas reduced results to 1430.
- Only peer-reviewed journal articles and review papers were included, reducing the dataset to 1043 publications.
- Articles in press or incomplete were excluded by limiting the publication stage to "final," resulting in 1014 publications.
- Only publications from journal sources were included, narrowing the dataset to 1011 publications.
- Non-English publications were excluded, yielding a final dataset of 995 publications, which were then imported into an Excel spreadsheet for further detailed screening.

Table 1 Inclusion and exclusion criteria

Criterion	Inclusion criteria	Exclusion criteria
Topic relevance	Studies addressing climate change and agricultural productivity	Studies unrelated to these topics
Publication type	Peer-reviewed journal articles and review papers	Non-peer-reviewed articles, conference papers, dissertations, or articles in press
Language	English-language publications	Publications in other languages
Publication date	Articles published from 2015 onwards	Articles published before 2015
Quality standards	Articles scoring above the minimum threshold in quality assessment	Articles below the quality assessment threshold

During the process, 18 duplicate articles were removed, leaving 977 unique studies. After title and abstract screening, 890 irrelevant papers were excluded. The remaining 87 studies underwent full-text assessment using Kitchenham's quality criteria, resulting in the exclusion of 56 articles that did not meet the inclusion threshold (see Appendix A for details). The final selection included 49 studies, with 28 additional articles added to strengthen the review, bringing the total to 77 studies. This rigorous selection process ensured the inclusion of high-quality, relevant, and methodologically sound studies.

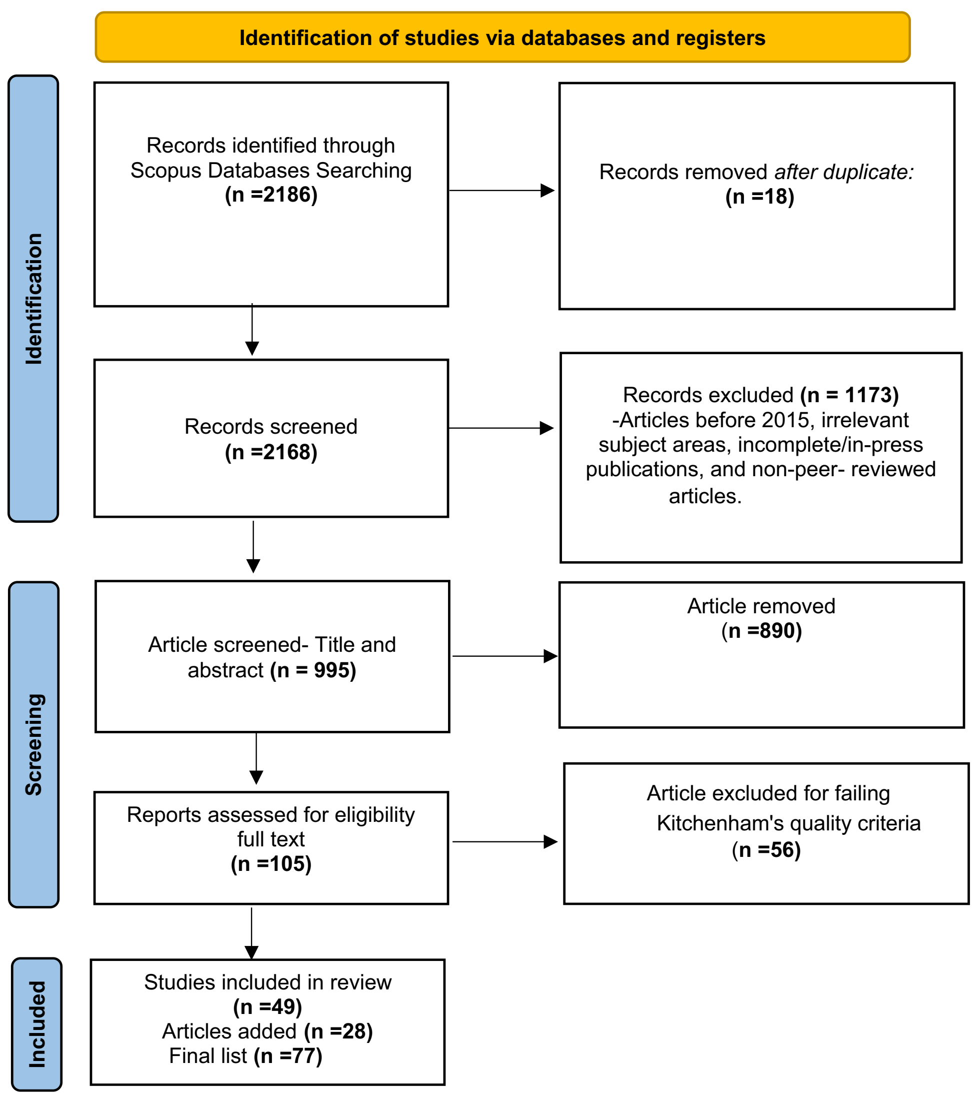
3 Analysis and result

After the quality assessment, 77 articles satisfied the inclusion criteria and were included in the study. These articles provide a well-curated dataset that offers relevant and high-quality insights into how climate change affects agricultural productivity. A descriptive analysis was conducted to identify key trends and patterns in the existing literature, providing a comprehensive overview of the research landscape (Fig. 1).

3.1 Publication trends, leading contributor countries, and top-cited journals

The Fig. 2 illustrates the publication trends in climate change and agricultural productivity research from 2004 to 2024. Notably, there is a significant upward trend in the number of publications over the years, particularly from 2019 onwards. This

Fig. 1 PRISMA flow diagram for study selection process [42]



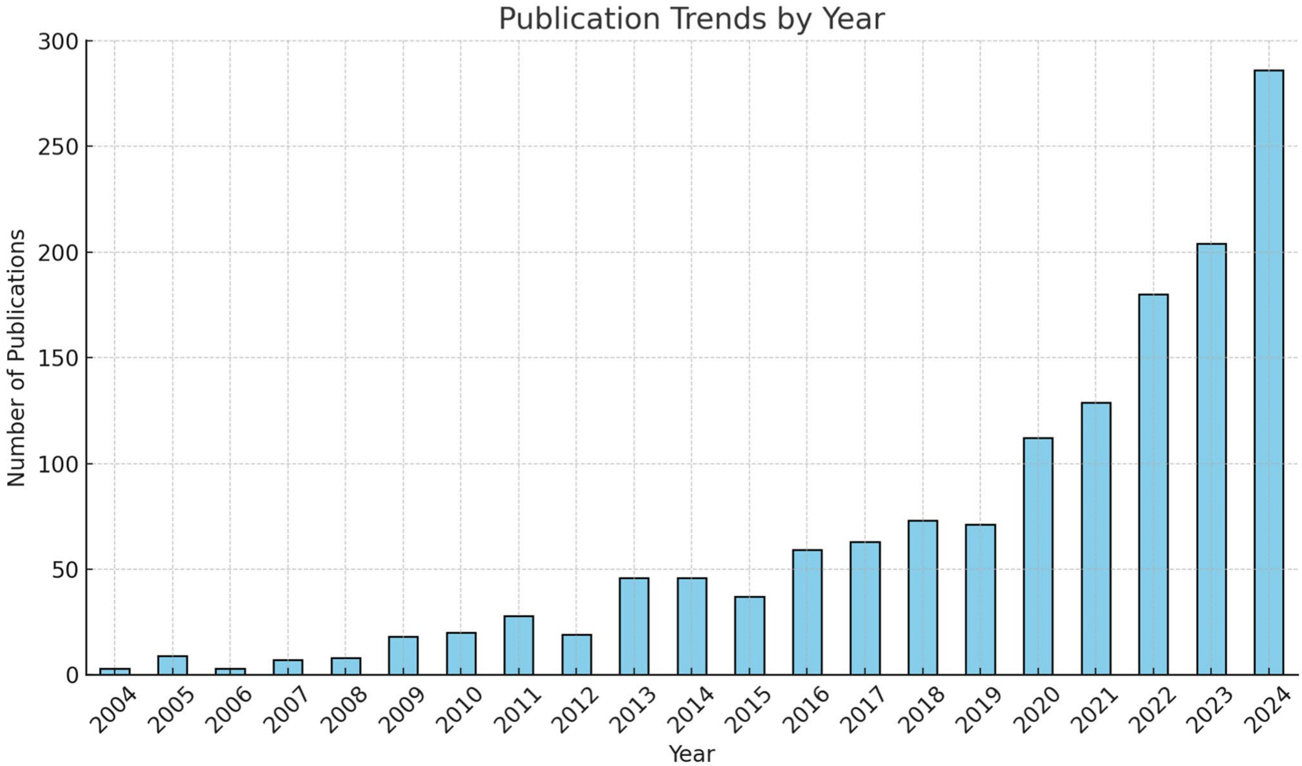


Fig. 2 Publication Trends by year

increase may reflect a growing global emphasis on addressing climate change impacts on agriculture due to heightened awareness and the urgency of adapting agricultural practices in the face of changing climatic conditions. Publications have notably increased in the last 2 years, a trend likely driven by recent climate events and increased funding for sustainable agricultural practices. This underscores the urgent and growing need for research in this critical area.

Figure 3 illustrates the global distribution of research contributions, particularly in climate change and agricultural productivity. India leads prominently with 302 mentions, underscoring its pivotal role in global research. Germany and China follow with 259 and 179 mentions, respectively, highlighting their substantial impact and active engagement. The United Kingdom and Canada are also key contributors, with 125 and 113 mentions, affirming their strong academic presence.

Additionally, Australia, Italy, and Ethiopia are actively involved, contributing 110, 74, and 71 mentions, respectively. France, with 29 mentions, although smaller in scale, plays a vital role in the research landscape. This distribution clearly reflects the extensive and varied engagement of these countries in important research areas, demonstrating the depth of their contributions globally.

The Fig. 4 illustrates the "Top-Cited Journals in Climate Change and Agricultural Productivity Research," detailing the total citations per journal to highlight their influence within the research community. "Science of the Total Environment" leads with 1200 citations, showcasing its significant role in impactful research. Following closely are "Sustainability (Switzerland)" and "Nature Climate Change" with 1000 and 800 citations respectively, both crucial for advancing research on climate change and agriculture. Additional journals include "Journal of Cleaner Production" with 750 citations, "Agricultural Water Management" with 700, "Environmental Research Letters" with 650, "Land" with 600, "Agronomy" with 500, "Plants" with 400, and "Frontiers in Plant Science" with 350 citations. This lineup underscores the range and depth of journals contributing to this vital field.

4 Thematic analysis

This section reviews key themes in the literature on climate change's impact on agricultural productivity. It covers topics such as the effects of climate change on agriculture, soil and water resource management, adoption of climate-smart practices, socioeconomic impacts, food security under climate stress, technological and policy innovations, and regional and global implications.

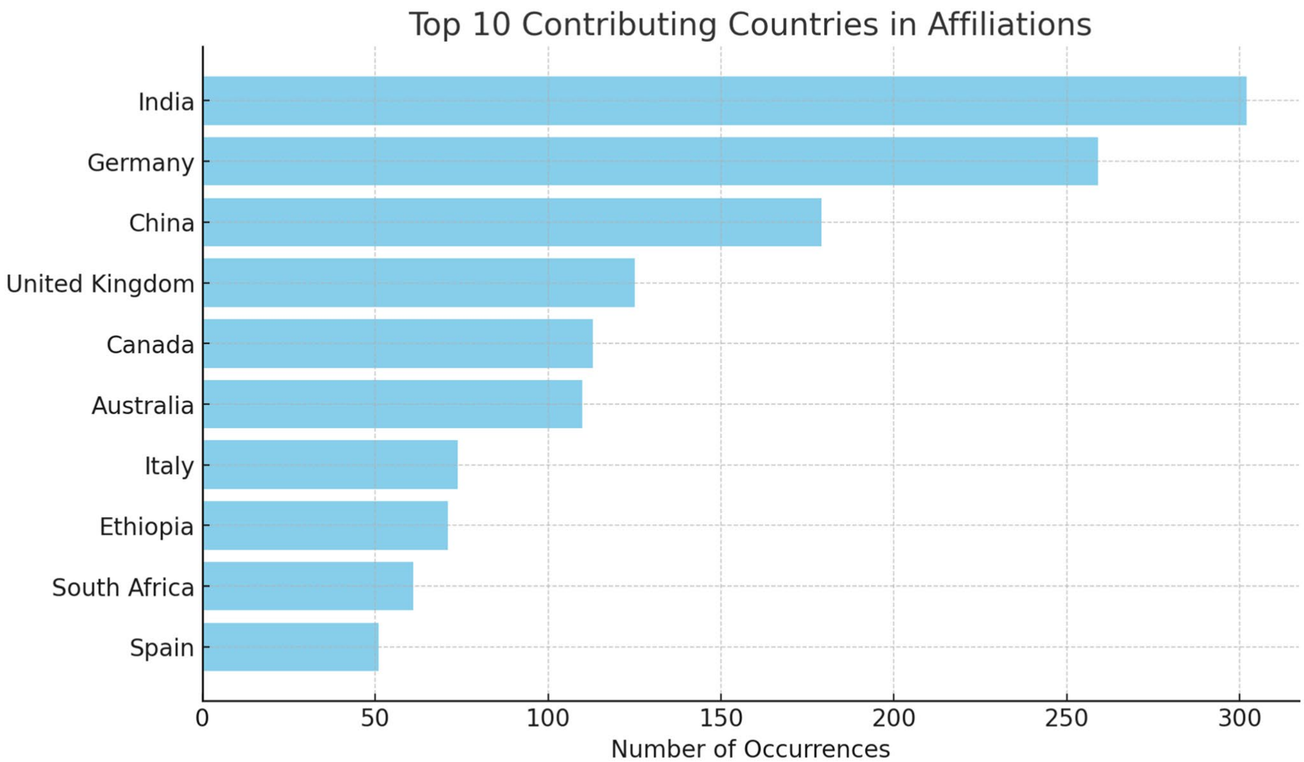


Fig. 3 Most contributing countries

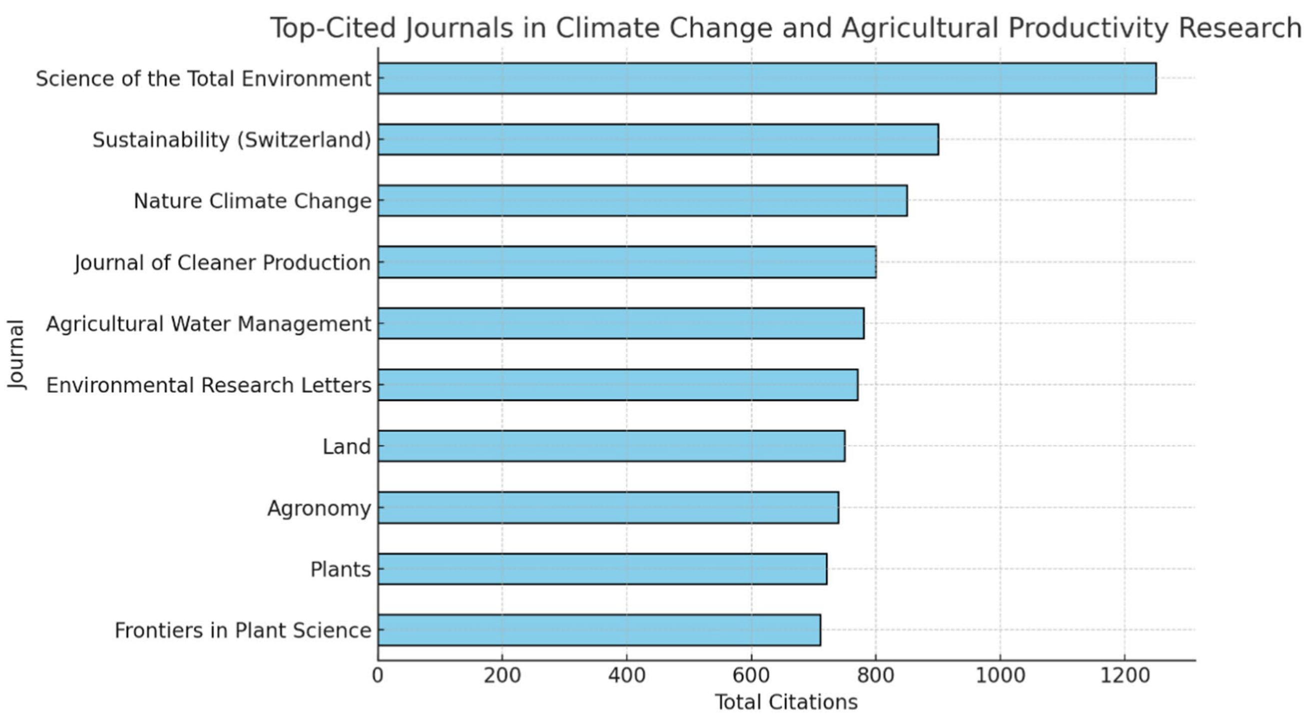


Fig. 4 Top-Cited Journals

4.1 Climate change and agricultural productivity

Climate change poses a severe threat to global agricultural productivity, with rising temperatures, shifting precipitation patterns, and extreme weather events leading to substantial declines in crop yields. Research indicates that a 1 °C increase in temperature reduces global wheat production by 6% [5]. In the United States, a 2 °C temperature rise decreases sorghum yields by 24% and reduces heat tolerance in sorghum by 70%, rendering traditional crop varieties increasingly unsuitable [39].

The impact of climate change varies across regions. In Brazil, global warming is projected to reduce agricultural output per hectare by 18%, with regional variations ranging from – 40 to + 15%, depending on climate resilience and adaptation capacities [6]. In India, maize yields under irrigated conditions are expected to decline by 10.58–23.39% from 2021 to 2050 and 15.20–26.83% from 2051 to 2080, primarily due to rising temperatures and climate variability [53]. In Vietnam, rainfed rice yields in the Mekong River Delta could decline by 24% in winter, 49% in summer, and 36.5% annually. However, irrigated rice yields may decline only by 1.78% annually, with winter rice decreasing by 4.7% and summer rice slightly increasing by 0.68% [24]. Eder et al. [15], examining cereal farms in Austria, found that rising temperatures and rainfall variability significantly reduced yields.

Developing regions are particularly vulnerable. In sub-Saharan Africa, extreme weather events such as floods and droughts significantly reduce yields of staple crops like maize, rice, and sorghum [3]. In Ethiopia, barley and sorghum are among the most affected crops, with precipitation variability exacerbating food insecurity [10]. Rising malaria prevalence, driven by climate-induced temperature and rainfall fluctuations, contributes further to a 2.6% reduction in cereal yields as health-related disruptions lower agricultural labor productivity [31].

In Benin, [14] analyzed the impact of climate change on cereal production using SARIMA time-series models and the PLS-SEM approach. Their findings indicate that rising temperatures and declining precipitation are negatively affecting cereal yields. However, Beninese farmers have responded by expanding cultivated areas, leading to increased overall production. Projections for 2050 suggest continued growth in maize and rice production, while sorghum output is expected to remain stable. These trends highlight the adaptability of farmers in the region but also underscore the need for long-term resilience strategies to sustain agricultural productivity in the face of climate change.

Beyond direct yield losses, climate change accelerates soil erosion, further threatening agricultural productivity. Yang et al. [63] found that rising temperatures and extreme weather events intensify soil erosion, leading to nutrient depletion, restricted root development, and reduced crop yields. In China, Guo et al. [18] observed maize yield declines of 9–22% due to soil erosion, while globally, Carr et al. [11] reported an annual decline of 3% in corn and wheat yields between 1980 and 2010 due to erosion. Gao et al. [17] further highlighted that soybean yields decrease by 5.97% per 10 cm of topsoil loss, worsening to a 9.44% loss in the top 40 cm layer. Reduced soil depth limits nutrient absorption and root growth, making crops more susceptible to drought and extreme weather [18].

Another major consequence of climate change is increased pest infestations, significantly impacting crop yields. Deutsch et al. [12] found that for every 1 °C rise in temperature, pest-induced crop losses increase by 10–25%. Rising temperatures and changing humidity accelerate pest reproduction and migration, exacerbating agricultural vulnerabilities.

Tangible effects of these climatic changes have already been observed in agricultural regions. Between 2017 and 2021, Kanj et al. [25] conducted direct interviews with farmers in Lebanon and employed XLSTAT statistical analysis to assess climate change's impact on local agriculture. Their findings revealed a 25% decline in cultivated land, primarily due to rising temperatures intensifying pest infestations and reducing crop yields. These trends are not limited to Lebanon but have become a global concern, as pests and pathogens continue adapting and expanding into new geographic regions. Lahlali et al. [32] observed that insects, fungi, and plant pathogens now thrive in previously uninhabitable areas, posing an escalating threat to food security. Staple crops such as wheat, maize, and rice—critical to global food supply—are particularly vulnerable to pests like aphids, locusts, and borers, leading to severe yield reductions, economic instability, and increasing food insecurity [32].

To counteract the worsening impacts of climate change on agriculture, implementing sustainable mitigation strategies is essential. Among these, reforestation has emerged as highly effective due to its ability to sequester carbon, restore ecosystems, and regulate hydrological cycles [33, 63].

Beyond carbon sequestration, reforestation enhances water availability, particularly in drought-prone regions, by improving evapotranspiration, precipitation patterns, and soil moisture retention [56]. A notable example is China's

Loess Plateau, where large-scale afforestation since 1999 has increased vegetation coverage by 3.15% per decade and raised precipitation by 54.62 mm [57]. These initiatives reinforced soil moisture-vegetation-precipitation feedback loops, improved regional rainfall distribution, stabilized soils, and strengthened agricultural resilience. Table 2 summarizes key themes on climate change and agricultural productivity, outlining studies on climate variability's impact on crop yields, soil health, and adaptation strategies.

4.2 Climate change and food security

Climate change presents a major challenge to global food security, exacerbating hunger, malnutrition, and economic instability. Dijk et al. [13] conducted a systematic review and meta-analysis of 57 global food security projection studies to assess the long-term impacts of socioeconomic and climate change scenarios. Their findings indicate that global food demand will rise by 35–56% by 2050, primarily due to population growth and economic expansion. Without climate change, the population at risk of hunger could decrease by up to 91%, although socioeconomic disparities could still lead to an 8% increase in hunger in some cases. However, with climate change, hunger levels could rise by up to 30% due to climate-induced crop failures, food supply chain disruptions, and extreme weather events.

Mirzabaev et al. [40] conducted a literature review and risk assessment to evaluate the impact of climate-related risks on food security and nutrition, particularly among vulnerable populations. Their study found that climate extremes—such as droughts, floods, and rising temperatures—worsen food insecurity and malnutrition, especially in low-income and marginalized communities lacking the resources to adapt.

Lloyd et al. [35] used statistical modeling across 44 countries to examine how climate change affects child stunting through interactions with income and food prices. Their findings indicate that without climate change, child stunting cases could reach 110 million under a poverty scenario and 83 million under a prosperity scenario by 2030. However, climate change could add between 570,000 and 1 million additional cases, with rural areas being the most affected due to income disparities and sensitivity to food prices.

As global temperatures rise, food production capacity is projected to decline significantly, particularly in developing regions. Beltran-Peña et al. [7] estimate that under a 3 °C temperature increase, Africa's food production capacity will sustain only 1.35 billion people, while its population is projected to reach 3.5 billion, creating a food deficit for 2.15 billion people.

Kompas et al. [29] further project that under various climate scenarios, global food production could decline by 6%, 10%, and 14% by 2050, exacerbating food insecurity and economic instability.

If climate change mitigation measures are not implemented, declining crop yields will increase food prices, negatively impacting agricultural welfare and global economic stability. Stevanović et al. [55] estimated that the global economy could suffer a 0.3% annual GDP loss by 2100 due to climate-related agricultural disruptions. However, with effective mitigation policies, the impact on food prices and economic stability could be significantly reduced, lessening the burden on vulnerable populations. Table 3 illustrates key themes related to climate change, agricultural welfare, and food security.

4.3 Soil and water resource management

Soil and water resource management plays a critical role in enhancing agricultural productivity by improving soil health, optimizing water efficiency, and increasing crop yields [54]. One of the most effective conservation strategies is cover cropping, which helps reduce soil erosion, strengthen soil structure, and preserve soil fertility.

Koudahe et al. [30] found that cover crops significantly enhance soil health and boost productivity by improving fertility, reinforcing soil structure, and increasing water infiltration. Acharya et al. [1] further support these findings, demonstrating that cover crops promote soil aggregation, mitigate degradation, and enhance nutrient retention, ultimately contributing to a more resilient and sustainable agricultural system.

Beyond these immediate benefits, cover cropping plays a crucial role in long-term soil health by increasing soil organic carbon (SOC) levels by 13–17%, which enhances soil fertility and improves crop productivity [1]. Liu et al. [34] highlighted the strong correlation between SOC enrichment and increased crop yields, while Oldfield et al. [45] found that increasing SOC improves maize yields by 10% and wheat yields by 23%. Additionally, higher SOC reduces fertilizer dependency, enhances soil sustainability, and strengthens agricultural resilience, reinforcing its critical role in ensuring long-term food security.

Water resource management is pivotal in enhancing agricultural productivity, particularly through practices such as efficient irrigation and rainwater harvesting. Efficient irrigation ensures that crops receive the optimal amount of water,

Table 2 Climate Change and Agricultural Productivity Modeling

Theme	Author(s)	Methodology	Key findings	Implications
Climate Change Impact on Crop Yields	Asseng et al. [5]	Crop modeling, field experiments	Wheat yields decline by 6% per 1 °C increase; models struggle with higher temperature accuracy	Highlights the need for improved climate-resilient wheat varieties and refined predictive models
	Assunção & Chein [6]	Cross-sectional analysis, IPCC projections	Brazil's agricultural output expected to decline by 18%, with regional variations (-40% to + 15%)	Calls for region-specific adaptation strategies to mitigate risks
	Miller et al. [39]	Panel data regression (38-year farm data)	A 2 °C temperature rise leads to a 24% reduction in US sorghum yields; weak adaptation evidence	Emphasizes the need for improved seed varieties and modernized farming techniques
	Jiang et el 2019	DSSAT model with WRF-downscaled CMIP3 projections for the Mekong Delta, Vietnam	- Rainfed conditions: Winter rice yield may decline by 24%, summer rice by 49%, and overall annual yield by 36.5%	Policymakers must implement climate-resilient agricultural policies for long-term food security
	Dosa et al. (2024)	SARIMA time-series, PLS-SEM analysis	Rising temperatures and declining rainfall impact cereal production in Benin. Farmers are expanding cultivated areas, boosting yields. Maize and rice production are projected to increase by 2050, while sorghum remains stable	Understanding resilience strategies is crucial for shaping future agricultural policies and adaptation measures
	Srivastava et al. [53]	CERES-Maize model simulation for eastern India using RCP scenarios	- Irrigated conditions: Maize yield is projected to decline by 10.58–23.39% (2021–2050) and 15.20–26.83% (2051–2080) compared to the baseline (1982–2012)	Policymakers must prioritize investments in climate-adaptive technologies and sustainable water management
	Praveenkumar et al. [49]	Crop simulation (CCSM4 data) Study on climate impact on Indian sorghum	Sorghum yields could decline by 1.3–30.5%. Fertilizer has minor benefits	Calls for improved seed varieties and resilient farming
	[3]	FMOLS; analysis of climatic variables and food crop yields in SSA (1990–2020)	Floods and droughts reduce maize, rice, and sorghum yields.	Advocates promoting agricultural insurance and adaptation measures to improve resilience
	Koudjom et al. [31]	SSA panel data, GMM regression	Rising malaria prevalence reduces cereal yields by 2.6%	Disease reduction strategies are critical for sustaining agricultural productivity
	[10]	Productivity function, Ricardian approaches; state-level analysis of four crops in Ethiopia (2011–2020)	Barley and sorghum are the most affected crops, with barley contributing to food insecurity	Recommends policy interventions and adaptation strategies
Soil Erosion and Its Impact on Crop Production	Guo et al. [18]	Field experiment (maize-soybean rotation)	Maize yield drops 9–22% with topsoil loss; soybean remains stable	Calls for improved fertilization and erosion control strategies
	Yang et al. [63]	Literature review		

Table 2 (continued)

Theme	Author(s)	Methodology	Key findings	Implications
Examining climate's impact on agriculture	Climate change accelerates soil erosion, pests, and GHG emissions, reducing productivity	Need for climate-resilient farming and mitigation strategies		
	Carr et al. [11]	EPIC crop model, global analysis (1980–2010)	3% yield loss for maize/wheat due to erosion; economic impact of $3.3B	
Urges stronger soil conservation policies in vulnerable regions				
Pest and Disease Management	Deutsch et al. [12]	Insect-crop modeling	Crop losses increase by 10–25% per 1 °C warming, especially in temperate regions	Highlights the need for enhanced pest control strategies in warming climates
	Kanj et el. [25]	Direct interviews with farmers in Lebanon; XLSTAT statistical analysis	Cultivated area decreased by 25% (2017–2021). Increased temperature exacerbates pests and reduces yields	Recommends addressing costs and resilience strategies
	Lahlali et al. [32]	Literature review	Rising temperatures and humidity increase plant disease virulence and reduce effectiveness of existing control strategies	Urges integration of climate-adaptive disease management in agriculture
	Mitra et al. [41]	Review article	Pesticide degradation leads to toxic byproducts (PTPs); current detection and regulation are insufficient	Calls for stricter environmental policies and improved detection technologies
Climate Adaptation and Mitigation	Wang et al. [61, 62]	CS-ARDL model (Asia, Africa, America, Europe)	A 1% rise in renewable energy increases agricultural productivity by 1.512% globally	Supports policies promoting renewable energy adoption to enhance agricultural sustainability
	Lavudya & Prabhakar [33]	Global review	Climate change negatively impacts agriculture; mitigation efforts include renewable energy, reforestation, and climate-smart food systems	Supports large-scale climate adaptation and policy shifts
	Teo et al. [56]	Climate modeling (2041–2070)	Reforestation improves water yield but may create imbalances in certain regions	Calls for careful moisture balance assessments before afforestation
	Gao et al. [17]	Experimental study with potted soybean trials under different soil erosion treatments	Yield reductions of 5.97% per 10 cm of soil loss, with a higher rate (9.44%) in the top 40 cm layer	Soil erosion significantly impacts agricultural productivity. Conservation practices, erosion control, and improved soil management are critical for maintaining crop yields
	Tian et al. [57]	Afforestation impact analysis (1999-present)	Large-scale afforestation increased vegetation cover by 3.15% per decade, improving precipitation and soil moisture retention	Supports sustainable afforestation policies to enhance long-term water availability

Table 3 Themes in climate change, agricultural welfare, and food security

Theme	Author(s)	Methodology	Key findings	Implications
Climate Change and food security	Stevanović et al. [55]	Climate and economic modeling using 19 projections	- Agricultural GDP loss may reach 0.3% by 2100 - Trade restrictions worsen losses, while CO_2 fertilization may offset damage	- Trade liberalization can reduce economic losses - CO_2 fertilization could help stabilize yields - Compensation policies are needed for vulnerable regions
	Mirzabaev et al. [40]	Literature review and risk assessment	- Climate extremes (droughts, floods, temperature changes) worsen food insecurity and malnutrition, particularly in low-income communities	- Urgent need for adaptation policies to mitigate food security risks
	Dijk et al. [13]	Systematic literature review and meta-analysis of 57 global studies	- Global food demand is projected to increase by 35–56% by 2050 - Population at risk of hunger may change by −91% to +8% (without climate change) and −91% to +30% (with climate change)	- Future food security projections must consider climate resilience strategies to safeguard food systems
	Lloyd et al. [35]	Statistical modeling using poverty and food price projections across 44 countries	- Climate change may cause 570,000 to 1 million additional stunting cases by 2030 - Rural areas are more affected due to income disparities and food price sensitivity - Rising food prices increase stunting in low-income countries but may reduce it in prosperous ones by supporting farmer incomes	- Focus on income security alongside food availability for climate adaptation - Balance food affordability and farmer livelihoods in policies - Employment and wage growth are key to reducing child undernutrition
	Beltran-Peña and D'Odorico [7]	Agro-hydrological, climate, and socio-economic models	- Irrigation alone is insufficient to meet food demand under a 3 °C warmer climate - Cropland expansion or imports may be needed, exposing populations to price volatility	- Policies must integrate irrigation with other strategies such as land expansion and trade stabilization
	Kompas et al. [29]	GTAP-DynW model with GTAP data for 141 countries	- Global food production is projected to decline by 6%, 10%, and 14% under respective scenarios - 556 M, 935 M, and 1.36B additional people could face severe food insecurity by 2050	- Urgent need for global adaptation policies to mitigate food insecurity - Climate policies should address water and heat stress to maintain food production

minimizing wastage while maintaining soil moisture levels necessary for healthy plant growth. This leads to more consistent crop yields, particularly in regions prone to drought or irregular rainfall. In areas facing climate-related challenges, efficient irrigation significantly improves crop productivity. Mamun et al. [36] found that farmers in coastal Bangladesh are increasingly adopting improved irrigation techniques, such as rainwater harvesting and more efficient water management practices, to counteract the impacts of drought and heat stress on crop production. Similarly, Fionnagáin et al. [16] demonstrated that irrigation projects in the Senegal River Valley led to a significant expansion of rice cultivation, particularly in regions directly targeted by these initiatives. Despite challenging drought conditions, the reliable availability of irrigation water ensured stable production and even facilitated the growth of cultivated areas. The economic impact was substantial, with a US$61.2 million increase in market value since the initiation of the irrigation projects in 2015. This underscores the critical role of irrigation in boosting rice productivity and generating significant economic benefits in the region.

Jia et al. [23] demonstrated that the application of high-efficiency water-saving irrigation (HEI) technologies resulted in substantial improvements in crop productivity. Specifically, their study observed a 69.99% increase in cotton yield, alongside a notable 55.27% improvement in crop survival rates. These findings underscore the effectiveness of HEI in enhancing agricultural output, particularly in environments where water scarcity and soil salinization are prevalent. Table 4 illustrates key themes related to soil and water resource management.

4.4 Climate-smart agriculture (CSA) on agricultural productivity and sustainability

Climate-Smart Agriculture (CSA) is a critical approach for improving agricultural productivity, food security, and resilience in response to climate change. By integrating sustainable farming practices, resource-efficient technologies, and climate adaptation strategies, CSA not only mitigates climate-related risks but also promotes long-term agricultural sustainability [2, 8, 58]. Recent empirical studies provide robust evidence of CSA's positive impact on productivity, profitability, resource efficiency, and environmental sustainability across various agricultural systems.

Bijarniya et al. [9] conducted a 3-year, multi-location, farmer-participatory trial to evaluate the impact of Climate-Smart Agriculture Practices (CSAPs) on crop productivity, economic profitability, and environmental sustainability in the rice–wheat system. The findings revealed that CSAPs increased productivity by 10.5% and profitability by 29.4%, while reducing irrigation water use by 39.3% and improving irrigation and water productivity by 53.9% and 18.4%, respectively. Additionally, greenhouse gas (GHG) emissions, global warming potential, and overall environmental footprints decreased by 43%, 56%, and 59%, respectively. These results demonstrate that CSAPs not only enhance farm profitability and productivity but also improve resource efficiency, contributing to sustainable agriculture and climate resilience.

Ahmed et al. [2] expanded this analysis by examining 461 Ethiopian households in the East Hararghe Zone using a multinomial endogenous switching econometric model. The study found that CSA adoption significantly improved food security, with food security increasing by 28% (low adopters), 43% (medium adopters), and 56% (high adopters). Similarly, nutrition security increased by 4.3%, 20%, and 19%, respectively. These findings emphasize CSA's role in ensuring dietary stability in climate-affected regions.

Tilahun et al. [58] conducted a cross-sectional survey of 384 Ethiopian households, incorporating focus group discussions and key informant interviews. They utilized principal component analysis and a multinomial endogenous switching regression model to assess the relationship between CSA adoption and food security. The study identified 18 CSA practices, categorized into five distinct packages. While 92.3% of households adopted crop management practices, only 11.2% implemented soil and water conservation measures. Households adopting all five CSA packages experienced significant improvements in food security, including a 41.2% increase in per capita annual food expenditure, a 39.8% improvement in the Household Food Insecurity Access Scale (HFIAS), and a 12.1% rise in the Household Food Consumption Score (HFCS). These findings highlight the importance of adopting a holistic approach to CSA implementation to maximize food security benefits.

Bhatnagar et al. [8] further reinforced CSA's positive impact on agricultural productivity and climate resilience. Their study demonstrated that CSA practices such as agroforestry, intercropping, mulching, crop rotation, and water harvesting significantly enhance crop yields, farmer incomes, and resource efficiency while reducing greenhouse gas emissions. This evidence underscores CSA's role in advancing sustainable and climate-resilient farming systems.

Mazumder [38] conducted a study on Climate-Smart Agriculture (CSA) adaptation strategies in four sub-districts of southern Bangladesh to evaluate their impact on food security and rural incomes. The study found that CSA adoption significantly enhances agricultural productivity, leading to improved food security and increased rural incomes. However,

Table 4 Themes in soil and water resource management

Theme	Author(s)	Methodology	Key findings	Implications
Soil and Water Resource Management	Srivastava et al. [54]	Literature review on soil management practices	Conservation agriculture, precision farming, and nutrient management enhance soil health. Policies shape sustainable practices	A holistic, science-policy approach is needed to optimize soil management for sustainability
	Acharya et al. [1]	Field study on cover cropping in silage systems	Cover crops improve soil aggregation, SOC, and nitrogen storage, supporting erosion-prone regions	Cover cropping is essential for soil conservation and improving productivity in dry regions
	Koudahe et al. [30]	Literature review on cover crops and soil health	Cover crops reduce soil bulk density, improve structure, and enhance water infiltration and nitrogen fixation	Long-term research is required to evaluate economic viability across different climates
	Oldfield et al. [45]	Quantitative modeling on SOC and crop yields	SOC increases maize (10%) and wheat (23%) yields while reducing fertilizer dependency	Increasing SOC supports sustainable intensification and reduces reliance on synthetic fertilizers
	Liu et al. [34]	Meta-analysis of 112 studies on SOC and GWP	Biochar boosts SOC sequestration (+30.72%) and reduces GWP (−23.94%) more effectively than straw incorporation	Biochar enhances soil fertility and climate resilience, making it ideal for climate-smart agriculture
	Mamun et al. [36]	FGDs, KIIs, and climatic analysis in Bangladesh	Farmers face dry conditions and erratic rainfall; adaptive measures include resilient crops, organic fertilizers, and irrigation	Improving access to irrigation and climate-resilient seeds can enhance adaptive capacity
	Fionnagáin et al. [16]	Satellite remote sensing on irrigation in Senegal	Irrigation projects increased rice yields and economic value ($61.2 M) but require long-term maintenance	Investments in irrigation infrastructure are necessary for long-term agricultural sustainability
	Jia et al. [23]	25-year study on HEI, soil salinity, and yield	HEI increased cotton yields (69.99%), improved survival rates (55.27%), and reduced soil salinity	HEI is a viable strategy for improving soil and water management in saline-prone areas

the effectiveness of CSA is influenced by factors such as age, education, family size, farm size, and contact with agricultural extension officials, and prior training experience.

Adimassu et al. (2025) conducted a meta-analysis of 220 peer-reviewed articles to evaluate the impact of CSA practices on productivity, adaptation, and mitigation in Ethiopia's agroecological regions. The study identified over 20 CSA practices, most of which demonstrated positive effects on productivity, soil health, and carbon sequestration.

Miassi et al. [37] applied Data Envelopment Analysis (DEA) and the Tobit model to assess the effectiveness of energy allocation methods among maize growers in Benin. The study found that increasing agricultural input utilization enhances technical efficiency while maintaining yields, with labor input contributing the highest efficiency. Additionally, input augmentation was shown to improve scale efficiency. Key factors influencing efficiency included age, farming experience, production area, insecticide use, and NPK fertilizer application. However, challenges such as limited access to improved seeds, machinery, and financial resources hinder efficiency gains. These findings align with broader efforts to enhance agricultural resilience in sub-Saharan Africa, where extreme weather events are frequent. Strengthening land tenure systems and promoting CSA adoption through rental markets have been proposed as strategies to improve efficiency and climate adaptation [59]. Similarly, in semi-arid regions like Karnataka, India, CSA intensification has significantly increased farmer incomes, demonstrating its potential as a viable strategy for addressing climate vulnerabilities [26]. By integrating efficient input use with CSA practices, smallholder farmers can optimize productivity while building resilience against climate risks.

At a global level, the integration of CSA practices with sustainable intensification and climate adaptation policies offers a path toward resilient agricultural systems [51]. Strategies such as emission reduction, improved water management, and enhanced crop resilience are crucial for ensuring long-term food security in the face of climate change. Table 5 presents key themes in Climate-Smart Agriculture (CSA) Practices and Their Impacts.

4.5 The role of socioeconomic factors in climate change

Climate change is not only an environmental issue but also a socioeconomic challenge, with factors such as income, education, financial stability, institutional support, resource access, and technology playing crucial roles in mitigation, adaptation, and resilience. Kapoor and Deb Pal [26] highlighted that in India, education, landholding size, and financial stability significantly influence climate-smart agriculture (CSA) adoption. Farmers with larger landholdings and higher education levels are more likely to adopt CSA practices, enhancing agricultural productivity and resilience.

At the household level, Okolie et al. (2022) examined how socioeconomic factors affect climate change adaptation strategies. They found that higher education and stable financial conditions significantly enhance households' capacity to adapt effectively. Similarly, Novotny et al. [44] emphasized the critical role of institutional support and infrastructure in enabling effective climate adaptation strategies in Togo.

Ahmed et al. [2] demonstrated that gender, education, and market access significantly influence CSA adoption, with households adopting higher levels of CSA practices reporting up to a 56% improvement in food security. However, inadequate financial support and poor infrastructure remain major barriers, particularly in rural areas.

In coastal Bangladesh, Palash et al. [46] examined conservation agriculture adoption, finding that training, income levels, and climate perception significantly influenced farmers' willingness to adopt conservation practices. Institutional support, regular monitoring, and capacity-building initiatives are essential for promoting conservation agriculture. Similarly, Bhatnagar et al. [8] found that education significantly contributes to CSA adoption, further emphasizing the need for targeted educational programs to enhance agricultural resilience. These findings underscore the importance of addressing socioeconomic barriers through comprehensive strategies, including improving education, financial resources, infrastructure, and institutional support, to build resilience and enhance adaptation to climate change. Table 6 presents key themes related to climate change, socioeconomic factors, and adaptation strategies.

4.6 Technological and policy innovations in climate risk mitigation

Technological innovations in precision agriculture are transforming farming systems by improving agricultural productivity, enhancing sustainability, and mitigating climate risks. These advancements integrate the Internet of Things (IoT), artificial intelligence (AI), big data analytics, drones, and smart sensors to optimize resource use, minimize waste, and reduce environmental impacts [27].

Table 5 Themes in climate-smart agriculture (CSA) practices and their impacts

Theme	Author(s)	Methodology	Key findings	Implications
CSA, Productivity, food security, agriculture resilient	Bijarniya et al. [9]	Farmer participatory trial (3 years)	CSA increased productivity (10.5%) and profitability (29.4%), reduced water use (39.3%) and emissions	CSA improves sustainability and food security, recommended for Eastern IGP and similar regions
	Ahmed et al. [2]	Econometric model (Ethiopia)	CSA boosts food security (56%) and nutrition (19%). Adoption depends on education, extension services, and climate awareness	Strengthening education and extension programs enhances CSA adoption and food security
	Tilahun et al. [58]	Survey and FGDs (Ethiopia)	18 CSA practices identified; crop management (92.3%) most common. Higher food security in households adopting all five CSA types	Combining CSA with farm size, gender, and productive assets improves food security
	Bhatnagar et al. [8]	Thematic analysis	CSA boosts yields, income, efficiency, and resilience. Adoption influenced by education, land tenure, and credit access	Policies promoting land security, financial access, and education support CSA adoption
	Mazumder and Kabir [38]	Quasi-experimental study (2010–2018)	CSA improved food security and rural incomes	CSA financing is crucial for rural resilience and poverty reduction
	Adimassu et al. (2025)	Meta-analysis (220 studies)	CSA improved productivity, soil health, and carbon sequestration. Drip irrigation and mulching reduced erosion but had high costs	Tax reforms for drip irrigation can enhance adoption and profitability
	[59]	Mixed methods, state-contingent theory, CSA land allocation analysis in SSA	CSA land allocation remains low, negatively trending over time. Rainfall shocks and land tenure security positively influence CSA. CSA adoption Enhance resilience	Calls for policies promoting CSA practices for adaptation and food security
	Kapoor and Deb Pal, 2024	Primary survey of 1466 farmers; multinomial logistic regression; CSA adoption analysis in Karnataka, India	CSA adoption improves farmers' income depending on adoption intensity	Recommends promoting technology intensification as a resilience-building package
	[50]	FGDs, expert consultations, household surveys, Stochastic Frontier Analysis	Climate-smart practices significantly improve technical efficiency for major crops, such as wheat	Recommends policy shifts to promote these practices for resilience-building
	Miassi et al. [37]	DEA, Tobit model	Efficient input use boosts technical and scale efficiency; labor input is most effective. Key factors: age, experience, farm size, insecticide, and NPK use	Addressing input constraints (seeds, machinery, finance) is crucial for productivity and resilience

Table 6 Socioeconomic factors and climate change adaptation themes

Theme	Author(s)	Methodology	Key findings	Implications
Socioeconomic Factors and CSA	Okunola et al. (2022)	Survey of 384 household heads; descriptive and inferential statistics	Climate adaptation strategies were mostly reactive rather than anticipatory. Education, income, house type, ownership, and age significantly influenced adaptation	Integrating climate adaptation policies and raising awareness is essential for strengthening household resilience
	Kapoor and Deb Pal [26]	Survey of 1466 farmers; multinomial logistic regression	Education, landholding size, and asset ownership are key predictors of CSA adoption, which positively impacts farmers' income	Policies should support CSA adoption by providing incentives, training, and financial assistance
	Ahmed et al. [2]	Multinomial endogenous switching econometric model; 2020/21 data from East Hararghe Zone, Ethiopia	CSA adoption increases food security by up to 56% and nutrition security by 19%. Adoption is influenced by gender, education, extension services, soil fertility, market information, and training	Strengthening CSA extension services and access to market information can enhance food security outcomes
	Novotny et al. [44]	Companion Modeling (ComMod) approach; participatory serious games in Togo	Farmers prioritize short-term needs like food security and education over long-term agricultural investments	Aligning interventions with farmers' immediate priorities can improve adoption rates of CSA and other sustainable practices
	Palash et al. [46]	Survey and factor analysis in coastal Bangladesh	Adoption is influenced by training, income levels, and climate perception. Institutional support and farmer engagement are key drivers	Regular monitoring, capacity-building programs, and targeted engagement strategies are necessary to promote conservation agriculture
	Bhatnagar et al. [8]	Thematic analysis	CSA adoption improves yields, income, resource efficiency, and resilience. Key factors include education, household size, farming experience, land tenure, market access, technical training, and climate perception	Providing access to climate/weather information, technical training, and financial resources is essential to scaling CSA adoption

Karunathilake et al. [27] reviewed recent innovations in precision agriculture, highlighting IoT-based smart farming, AI-driven decision support systems, and remote sensing technologies as key drivers of efficiency. Their study found that these technologies significantly improve agricultural productivity and resource management.

Advancements in biotechnology have also contributed to climate resilience through the development of drought-resistant crop varieties using genetic modification (GM) and CRISPR/Cas9 technology. Hamdan and Tan [19] found that CRISPR/Cas9 faces less public resistance than traditional GMOs and has gained significant research interest for its potential in developing climate-resilient crops. These advancements have enabled the creation of heat- and drought-tolerant crop varieties, reducing yield losses in water-scarce regions.

Transitioning to renewable energy sources such as solar, wind, and bioenergy is another critical step in reducing greenhouse gas (GHG) emissions while promoting energy efficiency in agriculture. Wang et al. [61, 62] found that a 1% increase in renewable energy consumption (REC) improves global agricultural productivity by 1.512%, with regional productivity increases of 1.254% in Asia, 1.654% in Africa, 0.897% in America, and 1.325% in Europe.

Additionally, climate risk mitigation technologies such as early warning systems [28] and satellite remote sensing [16] provide essential tools for anticipating and adapting to climate variability. These innovations help farmers manage drought risks, extreme weather events, and shifting climatic conditions, reducing uncertainty in agricultural production. For instance, localized early warning systems in Botswana successfully integrated climatic and socioeconomic data to predict drought risks, offering a scalable model for other climate-vulnerable regions [28].

Governments and international institutions are increasingly implementing carbon pricing mechanisms to incentivize emissions reduction and promote green technologies. Policies such as carbon taxes and cap-and-trade programs encourage industries to limit their carbon footprints by assigning economic value to GHG emissions. These are among the most widely used policy tools in the global effort to achieve net-zero carbon emissions [47].

Hayo and Hasegawa [20] found that carbon credits effectively mitigate GHG emissions while boosting agricultural productivity. Their study highlights that climate-smart agriculture (CSA) practices, such as reducing fertilizer use and improving livestock management, lower methane and nitrous oxide emissions, demonstrating the dual benefits of emission reduction and productivity enhancement.

Governments worldwide are integrating CSA principles into national agricultural policies to enhance productivity and climate resilience. Policies promoting agroforestry, conservation agriculture, and diversified cropping systems have proven effective in mitigating climate risks and sustaining food security [51]. In sub-Saharan Africa, land tenure reforms and CSA adoption through rental markets have significantly increased agricultural resilience [59].

Trade liberalization and international cooperation are crucial for stabilizing global food markets amid climate uncertainties. Stevanović et al. [55] emphasized that removing trade restrictions can mitigate economic losses caused by climate change, as unrestricted trade facilitates the efficient allocation of food resources across regions.

Moreover, climate adaptation frameworks, such as the Paris Agreement and the United Nations Sustainable Development Goals (SDGs), provide a global roadmap for climate resilience. These frameworks urge nations to implement sustainable agriculture, reforestation programs, and emission reduction policies to create climate-resilient food systems [13]. Table 7 illustrates themes related to Technological and Policy Innovations in Climate Risk Mitigation.

5 Research implications

This research has significant implications for multiple stakeholders, including policymakers, researchers, agricultural practitioners, and international organizations. By synthesizing diverse studies, it enhances existing knowledge on climate adaptation in agriculture and provides a comprehensive analysis of how climate change affects agricultural productivity. One of the key theoretical contributions of this study is its challenge to the assumption that adaptation strategies produce uniform results across different agricultural regions. Instead, the review highlights how socioeconomic factors, governance mechanisms, and technological advancements interact with climate stressors to shape adaptation outcomes. This understanding deepens the theoretical discourse on climate resilience and underscores the importance of localized adaptation strategies tailored to specific agro-ecological zones.

The study also has methodological implications. Many existing studies rely on quantitative climate models and econometric analyses, which may not fully capture the complexities of real-world agricultural adaptation. This research emphasizes the need for a mixed-methods approach that integrates advanced climate modeling with qualitative insights from farmers, policymakers, and stakeholders. By incorporating AI-driven predictive analytics, remote sensing data, and

Table 7 Technological and policy innovations in climate risk mitigation themes

Theme	Author(s)	Methodology	Key findings	Implications
Precision Agriculture and Smart Farming	Karunathilake et al. [27]	Review of recent advances in precision agriculture	IoT, drones, AI, and big data enhance agricultural productivity, but challenges include adoption barriers, data management, and costs	Addressing adoption barriers and optimizing data integration can enhance farming efficiency and sustainability
Genetic Modification and CRISPR in Agriculture	Hamdan and Tan [19]	Comparative analysis and bibliographic review	CRISPR/Cas9 technology faces less public resistance than GMOs, with shifting research priorities	Understanding both technologies can inform agricultural policies and responsible biotech adoption
Renewable Energy in Agriculture	Wang et al. [61, 62]	CS-ARDL model (Asia, Africa, America, Europe)	A 1% rise in renewable energy use increases global farm productivity by 1.512%	Renewable energy adoption enhances agricultural sustainability, efficiency, and cost-effectiveness
Drought Risk and Climate Adaptation	Kemper [28]	Statistical and machine learning techniques integrating climatic, remote-sensing, and socioeconomic data	SPI and SOI indices significantly impact crop productivity; integrating diverse datasets improves early-warning systems	Encourages ground-truthing and local partnerships for climate risk assessment and adaptation strategies
Irrigation and Agricultural Resilience	Fionnagáin et al. [16]	Satellite remote sensing and machine learning (2015–2023); irrigation project evaluation in Senegal	Irrigation projects supported by satellite remote sensing, have boosted rice cultivation despite droughts, generating $61.2 million in market value since 2015	Long-term infrastructure investments and sustainable irrigation policies are needed for resilient agrifood systems
Carbon Pricing and Emission Reduction Policies	Pan et el. [47]	Review of empirical and theoretical research on carbon taxes and ETSs	Carbon taxes and ETSs have strengths and weaknesses; a hybrid approach combining both mechanisms may enhance emissions abatement	Policymakers should consider hybrid carbon pricing models that balance economic efficiency and emissions reduction
Carbon Credits and Emissions Reduction in Agriculture	Hayo and Hasegawa [20]	Stochastic Frontier Analysis; South African agriculture emissions (1991–2020)	Carbon credits help reduce methane and nitrous oxide emissions while enhancing productivity	Farmer-centric carbon credit markets and tailored mitigation strategies are needed for sustainable emissions reduction
Climate-Smart Practices and Productivity	Sedebo et al. [50]	FGDs, expert consultations, household surveys, Stochastic Frontier Analysis	Climate-smart practices improve technical efficiency for crops like wheat and teff. Key determinants include education, extension services, and climate change awareness	Policy shifts should promote CSA practices to enhance resilience and efficiency in smallholder farming
Land Allocation to CSA Technologies	Tione et al. [59]	Mixed methods, state-contingent theory, CSA land allocation analysis in SSA	CSA land allocation remains low, with a negative trend over time. Rainfall shocks and land tenure security positively influence CSA adoption	Policies promoting CSA adoption and land tenure security are essential for improving adaptation and food security
Climate Change and Agricultural Welfare	Stevanović et al. [55]	Climate and economic modeling using 19 projections	Consumer losses exceed producer gains, leading to a reduction in global agricultural welfare. Agricultural GDP losses may reach 0.3% by 2100. Trade restrictions exacerbate economic losses, while CO_2 fertilization could partially offset damage	Trade liberalization can help reduce economic losses. CO_2 fertilization could stabilize yields, but compensation policies are needed for vulnerable regions

Table 7 (continued)

Theme	Author(s)	Methodology	Key findings	Implications
Global Food Security Projections	Dijk et al. [13]	Systematic literature review and meta-analysis of 57 global food security projection studies	Global food demand is projected to increase by 35–56% by 2050. Population at risk of hunger is expected to change by − 91% to + 8% (without climate change) and − 91% to + 30% (with climate change). Climate change has a moderate but significant effect on food security projections	Provides a benchmark for global food security projections. Highlights the need for policy interventions to mitigate hunger risks. Future projections must consider climate resilience strategies to safeguard food systems

longitudinal field studies, future research can enhance the accuracy of climate adaptation assessments and provide more actionable insights.

From a policy perspective, this research underscores the necessity for region-specific agricultural policies that incorporate climate resilience strategies. Policymakers can use these findings to develop targeted interventions, such as incentivizing sustainable farming practices, investing in climate-resilient infrastructure, and expanding financial support mechanisms such as agricultural insurance and credit facilities for farmers. Strengthening agricultural extension services is also critical to ensuring that farmers have access to the latest knowledge and tools for climate adaptation.

This research has practical implications for the agricultural sector. Farmers, particularly those in climate-vulnerable regions, can benefit from the insights provided in this review by adopting climate-smart agriculture (CSA) practices, improving water management techniques, and utilizing precision farming technologies. Extension services and training programs should be expanded to enhance farmers' ability to implement these strategies effectively.

On a global scale, this study highlights the need for increased collaboration among international organizations, research institutions, and governments to address the challenges of climate change in agriculture. Strengthening knowledge-sharing platforms and international research networks can facilitate the development of scalable adaptation models applicable across different regions. Investments in climate adaptation research and development, particularly in underrepresented regions such as Africa and Latin America, will be crucial for ensuring global food security.

6 Research limitations and future research

Despite its contributions, this study has several limitations that highlight the need for further research. One primary constraint is the reliance on secondary data from SCOPUS-indexed articles. While these articles provide valuable insights, they may not fully capture localized climate anomalies or micro-level agricultural variations. Climate change effects can differ significantly across regions due to specific environmental conditions, soil health, water availability, and local farming practices. Future research should integrate primary data sources, including field surveys, farmer interviews, and direct observations, to ensure a more nuanced understanding of how climate change impacts agricultural productivity at the local level.

Another limitation is the methodology used in many of the reviewed studies. Many rely heavily on climate projection models and econometric analyses, which, although valuable, may not fully account for uncertainties in future climate patterns. These models often depend on historical data and assumptions about future climate conditions, which can be influenced by unpredictable variables such as policy changes, technological advancements, and socioeconomic shifts. A combination of qualitative and quantitative approaches, incorporating participatory research methods, stakeholder consultations, and real-time climate monitoring, would enhance the robustness and applicability of findings.

The temporal scope of existing research is another key concern. Many studies in this review focus on short-term impacts of climate change, often covering only a few growing seasons or specific extreme weather events. However, climate change is a long-term phenomenon that unfolds over decades. Short-duration studies may not adequately capture gradual shifts in temperature, soil degradation, water resource depletion, or the cumulative effects of changing weather patterns on crop yields. Future research should prioritize extended longitudinal studies that track agricultural productivity and climate resilience over multiple decades to provide more comprehensive insights into long-term adaptation strategies.

Geographical representation in the reviewed studies is also uneven. Research on climate change and agricultural productivity is concentrated in regions such as India, Germany, and China, where extensive climate and agricultural data are available. However, many highly vulnerable regions, particularly in Africa and Latin America, remain underexplored. These regions are among the most susceptible to climate variability, yet limited research means policymakers and farmers lack region-specific adaptation guidance. Future research should address this imbalance by expanding studies into diverse agro-ecological zones, particularly in developing nations where climate adaptation is most urgent.

Furthermore, while this review highlights the role of socioeconomic factors and policy interventions in shaping agricultural adaptation, it lacks an in-depth examination of governance structures, financial mechanisms, and institutional frameworks. Effective climate adaptation in agriculture requires well-structured policies that provide financial support, infrastructure investments, and incentives for sustainable practices. Future studies should analyze how governance mechanisms—such as agricultural subsidies, insurance schemes, and regulatory policies—can either facilitate or hinder adaptation efforts. Additionally, understanding the financial constraints faced by smallholder farmers and the role of international organizations in supporting climate adaptation will be crucial for designing policies that enhance agricultural resilience.

7 Conclusion

This systematic literature review provides a comprehensive analysis of the complex relationship between climate change and agricultural productivity, synthesizing insights from SCOPUS-indexed studies published between 2015 and 2024. The findings highlight that rising temperatures, erratic rainfall, extreme weather events, soil degradation, and increasing pest infestations present significant challenges to global food security. Climate projections suggest that without adequate adaptation measures, global food production could decline substantially, with disproportionate impacts on smallholder farmers in regions such as Sub-Saharan Africa, South Asia, and Latin America.

A key theme of this review is the role of adaptation strategies—particularly Climate-Smart Agriculture (CSA), soil and water conservation techniques, and technological innovations—in mitigating climate-induced risks. Studies indicate that CSA practices have contributed to increased productivity, improved farm profitability, and reduced greenhouse gas emissions, suggesting their potential in enhancing agricultural resilience. However, widespread adoption remains hindered by financial constraints, inadequate infrastructure, and limited awareness, particularly in low-income regions.

The findings also emphasize the importance of policy interventions in strengthening climate resilience within the agricultural sector. Advances in satellite-based climate monitoring, AI-driven precision farming, and early warning systems offer promising tools for climate adaptation and risk management. However, the effectiveness of these technologies is contingent on governance structures, institutional support, and financial accessibility. Policy instruments such as carbon pricing mechanisms, climate-resilient subsidies, and sustainable land management policies have been identified as critical enablers of adaptation.

Despite these insights, several research gaps remain. Many existing studies rely on quantitative climate models and econometric analyses, which, while valuable, may not fully capture the complexities of real-world agricultural adaptation. Future research should integrate field-based studies, farmer perspectives, and real-time climate monitoring to provide a more nuanced understanding of localized climate impacts. Additionally, geographical disparities in climate adaptation research persist, with extensive studies conducted in countries like India, Germany, and China, while highly vulnerable regions—particularly in Africa and Latin America—remain underrepresented. Addressing this imbalance is crucial for developing inclusive and region-specific adaptation frameworks.

Overall, this review underscores the need for a holistic, interdisciplinary approach that integrates technology, socioeconomic factors, and policy frameworks to build climate-resilient agricultural systems. While progress has been made, coordinated efforts from policymakers, researchers, and international organizations are essential to bridge knowledge gaps, enhance access to adaptation resources, and promote sustainable agricultural practices. By prioritizing climate-smart policies, farmer education, and investment in adaptive technologies, the agricultural sector can strengthen its resilience to climate uncertainties and contribute to long-term global food security.

Author contributions Abdikarim Farah contributed to conceptualization, methodology, software, validation, analysis, investigation, resources, data curation, writing (original draft and review), visualization, and project administration. Dr. Mohamud Ahmed Mohamed contributed to proofreading, data curation, conceptualization, and validation. Dr. Osman sayid Hassan musse contributed to proofreading, data curation, and conceptualization. Bile Abdisalan Nor contributed to proofreading and data curation, and project administration. All authors have reviewed and approved the final version of the manuscript.

Funding The study acknowledges the financial support provided by SIMAD University.

Data availability No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate This article does not contain any studies with human participants performed by any of the authors.

Consent for publication Not applicable.

Generative AI use I have read and agree to comply with the springernature AI Policy. I confirm that in accordance with the Taylor and Francis AI Policy, I have used Generative AI tools, specifically **Paperpal** and **Grammarly**, during the preparation of my manuscript. The tools were used to enhance language clarity, grammar, and overall readability.

Competing interests The authors declare no competing interests.

Appendixes A Kitchenham quality assessment table

Study	Study credibility and validity	Data collection and analysis	Findings and interpretation	Relevance and contribution	Reporting quality
Harnessing compost and vermicompost for sustainable nematode management	2	2	1	1	1
A Review on Climate Change, Credit Risk and Agriculture	3	2	1	2	1
Impact of Technological Innovations on Agricultural Productivity in China	2	2	1	2	2
Foliar H_2O_2 Application on Drought-Stressed Tomato Plants	2	2	1	1	1
Agricultural Drought Indices Interactions in Köppen–Geiger Zones, Bangladesh	2	2	2	3	2
Agricultural Mechanization and Green Development in China	3	2	2	2	2
Life Cycle Assessment and Neural Networks for Sugar Beet Production	2	2	1	1	1
Agriculture's Role in Renewable Energy and Sustainable Development in Africa	2	3	2	3	2
Mitigation of Saltwater Intrusion via Freshwater Recharge	3	2	2	3	2
Soil Erodibility Mapping Using Remote Sensing in Indian Himalayas	2	2	1	2	1
Resilient and Inclusive Rural Transformation within Agrifood Systems	2	2	2	1	2
Soil Moisture Estimation using Sentinel-1 and Modified Dubois Model	2	2	1	1	2
Farmers' Perceptions on Sealing Techniques in Burkina Faso	2	3	2	2	2
Forest Cover Change and Livelihood Implications in Ethiopia	2	2	2	1	2
Rainfall and Erosivity Dynamics in Odisha, India	2	2	2	2	1
Integrated Agroforestry-Bioenergy Systems in Sub-Saharan Africa	2	2	1	2	1
Electrical and Agricultural Productivity in Olive Agrivoltaic System	2	2	1	1	1
Heat-Shock Proteins under Multiple Abiotic Stresses	2	2	1	1	1
Winter Soil Warming and Biomass Carbon Loss	2	2	1	1	2
Enhanced Rainfall Variability Observations in Kenya	1	2	1	2	1
Solar Radiation Trends in Bangladesh (1983–2022)	2	2	2	2	1
Precision Agriculture and Water Conservation in Arid Regions	3	2	2	2	2
Atmospheric CO_2 Fertilization Effect on Cereal Yields in Morocco	2	1	2	2	2
Concurrent Heat and Drought Stress Effects on Floral Development	2	1	1	2	1

Study	Study credibility and validity	Data collection and analysis	Findings and interpretation	Relevance and contribution	Reporting quality
Effects of Nano SiO_2, Nano TiO_2 and Nanocomposites on Maize Growth and Soil Health	2	2	1	2	1
Effects of Regenerative Agriculture Technologies on Productivity of Cowpea in Embu County, Kenya	2	2	2	2	2
Public Investment in Agri-Food System Innovation for Sustainable Development	2	2	1	2	1
Dynamic Impacts of Economic Growth and Other Factors on Carbon Emissions in Turkey	2	2	1	1	1
Seed Nutritional Quality in Lentil Under Different Moisture Regimes	2	2	1	1	1
Dynamic Nexus of Economic and Environmental Factors in the Philippines	2	3	2	1	1
Adaptation to Weather Fluctuations by Bangladeshi Smallholder Farmers	2	3	1	2	1
Climate Change and Labor Reallocation in India	2	3	2	3	2
Farmers' Awareness about Climate Change Mitigation and Adaptation via PLS-SEM	2	2	3	3	2
Soil Organic Carbon Stocks in Cropping Systems, Kiti Sub-Watershed, Benin	2	2	1	2	1
Salt-Affected Soils in Tanzanian Agriculture	2	2	1	1	1
Indigenous Biotic Rainfall Forecasting Adaptation in Western Zambia	2	2	1	2	1
Evaluation of Photosynthetic Efficiency of Yam Bean under Elevated CO_2	2	2	1	2	1
Agricultural Investments and Hunger in Africa: Contributions to SDG2	2	3	2	3	2
Agriculture Scenario with Changing Climate: Impacts and Strategies	2	2	2	3	1
Climate Services and Agricultural Productivity in Ghana	3	2	1	3	2
Microbes, Host Plant, and Soil Management in Plant Microbiome Manipulation	2	2	1	2	1
Satellite Data Assimilation for Water Storage Changes in South America	2	2	2	2	1
Agricultural Technologies and Green Revolution Potential in Africa	2	2	2	3	2
Agricultural Sustainability in Changing Climate Scenarios: Indian Perspective	2	2	2	4	2
Climate Change Impact on West African Basin Scale Irrigation	3	2	2	3	2
Land Trust Lessons from UK to US	2	2	1	2	1
Coping with Climate Change in Eastern Cape, SA	2	2	2	2	2
Meaning of Climate-Smart Agriculture to Global Alliance Members	3	2	3	3	3
Conservation Agriculture and Climate Resilience	2	2	2	2	2
Transparent Statistical Model for Rainfed Corn Yield Prediction	2	2	2	1	1
Methane and Nitrous Oxide Emissions from Rice Paddies	2	2	1	1	1
Soil Carbon Management Practices in Oyo, Nigeria	2	2	2	2	1
Drought Analysis in Northwest Africa using Satellite Remote Sensing	2	2	2	2	1
Land Use Change Impact on Temperature and Agriculture in Peshawar	2	2	2	3	2
Linking Risk Communication and Sustainable Climate Change Action	2	2	2	2	2
Economy-Wide Impact of Drought-Induced Productivity Losses	2	2	1	1	1

Please note that these articles were excluded as they did not meet the required quality assessment standards.

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