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A systematic review of recent estimations of climate change impact on agriculture and adaptation strategies perspectives in Africa

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Abstract

The systematic review using the PRISMA protocol aims to identify the observed and projected impacts of climate change on crop production and food security, water resources, and livestock and explores the perspectives of adaptation strategies employed to cope with this challenge across African countries. The review permits visualization in one scheme of the most recent various results of ongoing climate impact on agriculture and strategies across African countries. It enables the agricultural community and policymakers to consider it as they address climate change risks to agriculture, livestock, water resources, as well as food security. Overall results from 125 selected articles show that in the last four years, there has been a lack of research on climate change-related issues analysis in agriculture in some countries, especially in Northern Africa, Middle Africa, and Southern Africa. In the same regions, studies on the impact analysis on livestock, water, and management techniques are limited. Even though the agriculture sector is severely impacted by climate change, the effects can still be positive or negative depending on the products cultivated and the region. The various adaptation strategies implemented seem to be more effective when applied as a combination than a single application. However, some challenges including the lack of knowledge, limited input access, insufficient equipment, and financial constraints in strategy adoption exist. As climate change is a persisting and continuing fact getting worse over time, the adaptation strategies implemented today may require further improvement. Thus, our study suggests that more research should be done in this area to facilitate continuous improvement. Women's leadership is important in the adoption of sustainable adaptation strategies. The introduction of gender factors in the assessment of the effectiveness of climate change adaptation strategies and food security components is recommended. Also, serious research should be carried out to define the most impactful adaptation strategies according to the important staple growing crops by region to cope with climate change impacts in the African food system.

Keywords Climate change impact · Agriculture · Adaptation strategies · Africa · Systematic review

JEL Classification Q15 · Q16 · Q54

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1 Introduction

Climate change has been a reality for a long time now. Nowadays, it is recognized as a growing global threat phenomenon that raises enormous and unprecedented challenges to different economic sectors throughout the globe. Climate change, characterized by long-term extreme weather events such as high temperatures, infrequent or disrupted rainfall, flooding, new diseases, and drought, is a major daily challenge. Especially, these challenges are dire for the agricultural sector due to its strong dependency on environmental conditions and weather patterns (IPCC 2014). Despite low greenhouse gas emissions, Africa is especially one of the highly vulnerable continents to the adverse impacts of climate change, and its agricultural sector is particularly at risk. From the loss of soil fertility to lower crop yields, reduced incomes, and food insecurity, climate change poses a significant threat to the well-being of millions of rural poor and the continent's population as a whole (Zougmoré et al. 2016; FAO 2017). Changes in climate conditions such as temperature variability, precipitation patterns, and extreme weather events can disrupt agricultural productivity, water availability, food security, and sustainable economic development. Nevertheless, the agricultural sector plays a very important role and constitutes a livelihood strategy in most African countries (Collier and Dercon 2014). On average, it accounts for more than 50% of the active workforce and more than 25% of the continent's GDP (UNECA 2009; Coulibaly et al. 2020). Despite its importance to the economy, African agriculture is characterized by low levels of technologies, investment, and productivity, as well as high levels of weather-related risk and changing climate (Sonwa et al. 2016). In the African context, where agriculture serves as a primary livelihood for a significant portion of the population, the impacts of climate change can be especially profound (Beltran-Peña and D'Odorico 2022). The ability to adapt to climate change is crucial for maintaining livelihoods and ensuring food security for millions of people across the continent. The interplay between a changing climate and agricultural practices has the potential to reshape food security, economic stability, and rural livelihoods across the continent (FAO 2018). Consequently, there is a pressing need to understand the intricate relationship between climate change and agriculture in Africa and to identify effective adaptation strategies that can mitigate its negative repercussions.

Most of the scientific work has been done in the literature on the past and present impact of climate change on the agricultural sector, the future projections envisaged, and the strategies adapted to counteract the phenomenon of climate change (e.g. Chapman et al. 2020; Recha et al. 2022; MacCarthy et al. 2021; Critchley et al. 2023; Feleke et al. 2023). However, despite the considerable amount of attention devoted to this subject, there remains a research gap in the systematic analysis and synthesis of the existing literature on the impact of climate change on African agriculture and the related adaptation strategies. Although single research studies have often highlighted specific aspects of this complex issue, there is a lack of a complete overview that synthesizes the results of several studies. Furthermore, existing research often focuses on very specific regions, crops, or adaptation measures, thus resulting in a fragmented comprehension of the overall impact of climate change on African agriculture. In addition, there is always a need to update the analysis and results, as the climate is constantly changing. This systematic review aims to fill these gaps by critically analyzing and synthesizing the most recent published evidence on the understanding of the link between climate change and agriculture in Africa, with a particular focus on the various perspectives and strategies related to adaptation, identifying common trends, divergences, and gaps in the literature. By filling these gaps, the systematic review will contribute to the formulation of informed policies and strategies that strengthen the resilience of African agriculture in the context of the current climate challenges.

The central research questions of this systematic review are as follows: What are the well-documented impacts of climate change on agriculture in Africa? What adaptation strategies have been developed and implemented to address these impacts? What are the challenges associated with the application of adaptation strategies and the gaps in research studies on the subject? To answer these questions, this review article is intended to achieve the following specific objectives: analyze and synthesize the results of relevant articles investigating the impacts of climate change on agricultural practices, productivity, and sustainable livelihoods in various African countries; identify and classify the range of adaptation strategies that have been suggested, applied, or tested in response to the climate change-induced challenges facing the African agricultural sector; assess the effectiveness and limitations of different adaptation strategies in different contexts and highlight gaps in implementation or knowledge; highlight new research trends, gaps, and areas requiring further study in the area of the impact of climate change on African agriculture and corresponding adaptation strategies.

The systematic review was performed through an exhaustive literature search of academic databases, covering a wide range of studies that explore the intersections of climate change and agriculture in Africa. Research studies were selected on the basis of predefined inclusion criteria of PRISMA protocol, to guarantee a diverse and representative sample. Data extraction and synthesis followed a structured process to identify key common themes, impact categories, and adaptation strategies. The outcome of the review was a synthesis that illuminates the state-of-the-art understanding of the impacts of climate change on African agriculture and the efficiency of different adaptation strategies.

Following the introduction, the subsequent sections first describe the methodology used to carry out our study. Second, we examined the spatial characteristics of the selected paper. Third, we examined the multidimensional impact of climate change on different agricultural systems in African countries, including crop and livestock production and water resources. Fourth, we explored the various adaptation strategies that have emerged in recent years in response to the impact of climate change and considered the implications of these findings for the future of food security and sustainable development on the continent. Finally, we discussed the challenges and gaps and concluded with some key recommendations.

2 Methodology

2.1 Data acquisition

To conduct the systematic review, the PRISMA (Preferred Reporting Items for Systematic Meta-Analysis) protocol (Page et al. 2021) was followed (Fig. 1). A comprehensive search was carried out in prominent academic databases, including the Web of Science and Google Scholar. The search terms used to find the most relevant papers included: “Climate change impact on agriculture”, “Climate and adaptation strategies”, “Sustainable adaptation strategies”, and “Climate-smart agriculture”. In total, an initial set of 7662 articles were recorded from the research. 1104 duplicated papers were removed. After that, those studies that did not satisfy the inclusion criteria from the

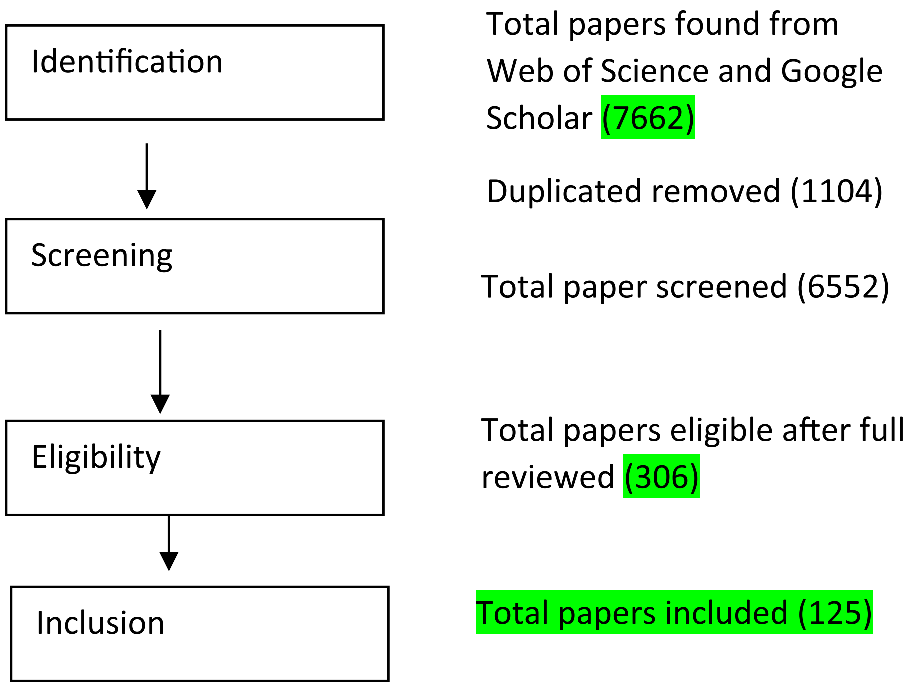

Fig. 1 Applied PRISMA protocol scheme

title and abstract screening were removed from the database. 306 papers have been fully reviewed and finally, 125 relevant papers were selected and included in the quantitative systematic review.

2.2 Papers selection criteria

To answer the questions about how climate change impacts the agriculture sector in African countries and the adaptation strategies that are being used, we have carefully selected relevant studies. To do so, consideration was given to only papers from reputable sources that had undergone peer review, and the first selection was based on titles, abstracts, and keywords. Data were extracted from these studies, including details on study characteristics, the geographic areas studied, the effects of climate change on agriculture, and the adaptation strategies implemented. To ensure the credibility of our paper and systematic review process, we excluded review articles, conference proceedings, book chapters, working and articles in press, and focused solely on peer-reviewed open-access published studies. Also, to ensure that recent studies are included, the search was restricted to articles published within the last four years (2020 to 2023). Additionally, we only considered papers written in English, as it is the most widely used and recognized language in scientific areas and published in highly impacted and peer-reviewed journals. These inclusion criteria enabled us to identify and select the most relevant articles. Find the inclusion, exclusion, and justifications in Table 1.

Table 1 Inclusion and exclusion criteria for articles in the review

Criteria	Inclusion criteria	Exclusion criteria	Justification of criteria
Topics	Articles on impact and Adaptation to climate change in agriculture	Papers not based on climate impact and adaptation	In order to stay within the research's parameters
Study area	African countries papers	Non-African countries articles	In order to keep the review focused on its intended subject
Language	English papers	Non-English papers	For the sake of clarity and based on researchers' expertise in the English language, readability will be improved
Publication date	2020–2023	Before 2020	To capture the most relevant recent papers
Article type	Peer-reviewed research journal article indexed in SSCI or SCI-EXPANDED	Book chapters, reviews, and conference papers	Interested in finding peer-reviewed empirical or original research that is available or original research
Availability	Fully available open-access papers	Non-available paper and paper in press	Due to not being open access, thereby requiring purchasing

3 Results and discussion

3.1 Spatial characteristics of papers included

The research has recorded many quantitative (with percentage and frequency estimation) and qualitative (evidence non-numeric but in-depth information transcription) studies in different geographical locations in Africa. Most of the papers were evidence from specific countries in Eastern Africa (49 papers), followed by Western Africa (34), Southern Africa (10), and Northern Africa (7) regions. Only a few founded studies were carried out in Middle Africa (5) (Fig. 2), while other articles have considered Africa as a whole or focused on multiple African countries (20) (Fig. 3). These papers showed evidence of climate change impact analysis on agriculture and livestock production and on water resources. Among the papers included, 10 have conducted analysis on the impact of climate change on livestock, while 8 have shown the link between climate change and water resources relaying the lack of scientific research in these areas during the last years. In the same way, articles including climate change adaptation strategies (Corp diversification, CSA, water, and livestock management strategies) assessment only 4 papers have shown evidence research on livestock management. The articles analyzed in this review are from journals in various disciplines related to climate, agriculture, meteorology, environment management, sustainability, animal, water, and health. *Sustainability* (MDPI journal) is the journal with the highest number of articles included (17 articles out of 125), followed by the Journal *Heliyon* (9 papers) and *Agriculture* (6 papers) and *Climatic Change* (6). The remaining articles come also from 5, 4, or 3, or 2, or 1 journal articles.

3.2 Climate change impact on agriculture in Africa

In Africa, farming practices mainly depend on traditional methods, rely heavily on rain-fed irrigation, and are sensitive to variations in temperature and rainfall (Chapman et al. 2020; Critchley et al. 2023). The inconsistency of these regimes affects crop yields in all regions,

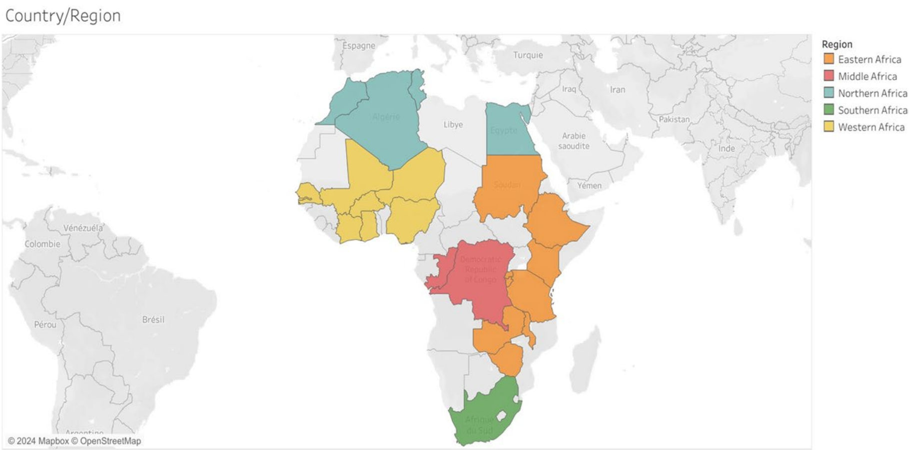

Fig. 2 Spatial distribution of the specific countries included

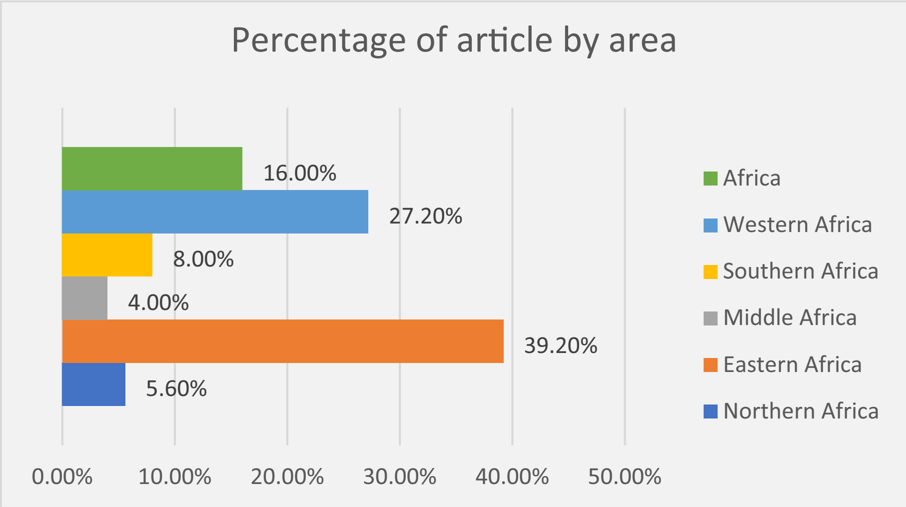

Fig. 3 Percentage of included paper by region

particularly in Africa, where significant variations are observed compared with other major regions of the world (Alvi et al. 2020). Crucially, the impacts of climate change on crop productivity in Africa may vary from region to region, owing to the vulnerability of rainfed crop production to climate change (Abahous et al. 2021; Bekuma Abdisa et al. 2022).

3.2.1 Crop productivity and food security

Researchers have shown that changes in temperature and rainfall influence planting seasons, crop growth, and yield which reduces food availability (e.g. Feleke et al. 2023; Bekuma Abdisa et al. 2022; Rettie et al. 2022; Ayal et al. 2023). Droughts and heat waves have become more frequent, leading to poor harvests and food shortages in vulnerable regions in African countries. In Ethiopia, Bekuma Abdisa et al. (2022) find that rainfall variability, minimum, and maximum temperature may affect positively and negatively the maize and sorghum yield cropping. For different regions of Ethiopia, the projection to 2030 estimated that the effects of climate change would be a 4% and 16% decrease in maize yield for Ambo and Melkassa respectively, while Bako would experience a 2% increase in maize yield (Feleke et al. 2023). However, wheat productivity will be more challenging, with a 36 to 40% reduction in its yields by 2050 (Rettie et al. 2022). In Gambella Zuria Woreda, the Southwestern part of the country, 67% of sampled households were found to be food insecure because of climate extremes (particularly floods and droughts) impact on crop production (Ayal et al. 2023). It is said that the diversity of Ethiopia's topography and landscapes make its crop production particularly vulnerable to climate change. In the central Welmera region for example, the studies predict a substantial decline in the yield of the Tumsa Faba bean variety up to 24.19% by mid-century under the high-emissions scenario RCP8.5 (Representative Concentration Pathway), while the Gora variety is forecast to record yield increases of 18.24% (under RCP4.5) and 28.03% (under RCP8.5) by mid- and end-century respectively (Bogale et al. 2021). Choi and Eltahir (2023) anticipate steady increases in temperature and rainfall during the growing season between 2021 and

2050 under certain climate scenarios. The impact of these changes on agriculture, however, varies from region to region, with potentially negative effects on agriculture in Sudan, mixed impacts in Ethiopia, and only marginal effects on crop growth in East Africa due to a weak humidification trend. Rainfed crop yields decrease by 15% and 14% for RCP 2.6 and 4.5, respectively, while they decrease by up to 32% for RCP 8.5 by 2100 in the tropical Gambella region in Ethiopia due to increased temperature, changes in soil water availability and atmospheric CO_2 concentration (Degife et al. 2021).

In addition, the study of Ginbo (2022) investigates the varying impacts of climate change on crop yields in Ethiopia across different crops and agroecologies. It predicts that climate change will also lead to increased coffee (31%) and teff (8.3%) yields at high altitudes by 2041–2060 but in contrast reduced coffee yields (3%) at low altitudes. Climate parameter trends have shown different variability in cereal yield (wheat, barley, millet) in Ethiopia as well (Yang et al. 2020). Another study found that while climate variability did not have a significant effect on overall crop production in Tanzania, it did have a considerable impact on maize production which is an important staple food crop in the country (Chegere and Mrosso 2022). Under current climatic conditions, around 4.3% of Zimbabwe's land is suitable for cocoyam production, the most suitable areas being in the eastern districts. However, climate change predictions point to a dramatic reduction in this suitability, varying from 6 to 15% by 2050 under different emissions scenarios, and a more pronounced reduction of 23% by 2070, with nearly a quarter of currently suitable areas becoming unsuitable for coconut production (Chemura et al. 2022).

Therefore, the impact of current and future climatic conditions on maize yields in Kenya differs according to various factors such as agroecological zones, type of soil, crop management, and climate change scenarios. In Western Kenya, evidence shows that climate change has reduced Maize crop yield and productivity (Kogo et al. 2022). In general, impacts are negative in low-potential agroecological zones, but positive in high-potential agroecological zones. However, if CO_2 fertilization is considered, the impacts of climate change become largely positive in all agroecological zones and management conditions in Kenya (Gummadi et al. 2020). Rainfall is expected to decrease, and in contrast, temperatures are expected to increase by 2050, which will have negative effects on crop yields and production, particularly on maize crops, in the southern and western regions of Zambia (Ngoma et al. 2021; Siatwiinda et al. 2021). The projection by Warnatzsch and Reay (2020) suggested that even though different sowing times and selection of slower-growing varieties could increase maize yields under higher rainfall scenarios, a minimal rainfall projection poses a risk of reducing yields in central Malawi. Maize, bush bean, and Irish potato production, which are key staple crops in Rwanda and form part of the country's crop intensification program, may suffer yield reductions of at least 10% under the RCP 4.5 and 15% under RCP 8.5 by the end of 2050. These reductions are expected to be greater in the drier eastern regions but could be neutral or even positive in the uplands up to the middle of the century (Austin et al. 2020).

In the Sudano-Sahelian zone of Ghana and Mali, current sorghum cultivation appears to be relatively vulnerable to climate change conditions (Adam et al. 2020). Soybean production is becoming more prominent in West Africa. However, the productivity in northern Ghana is being reduced by climate change, causing a decrease of 3 to 13.5% in soybeans (MacCarthy et al. 2022). Another study observed a decrease in rainfall and soil moisture in parallel with an increase in maize yields and temperatures. Individual climatic variables contributed varying percentages of the variation in annual maize yield, with soil moisture and temperature accounting for around 75% of the variation in wetter conditions and 40.8% in drier conditions (Atiah et al. 2022). Nonetheless, in Ghana, some areas are proven to be currently suitable for several crops, but under projected climatic conditions these areas will decrease, while areas with moderate and marginal conditions for several crops will increase, illustrating a spatial variation in crop production suitability across the country (Chemura et al. 2020).

Various regions in Nigeria have already experienced positive trends in rice yield, rainfall, and temperature pattern variability over the past 40 years (Akinbile et al. 2020). In contrast, Amare and Balana (2023) found that a 15% increase in adverse degree days led to an around 5% decrease in crop productivity on average, even after taking other factors into account over 30 years in Nigeria. Changes in rainfall also have a negative impact on crop production, especially for maize. Moreover, factors such as temperature variations, rainfall, arable land availability, and greenhouse gases such as CO_2, nitrous oxide, and methane have been pointed to have a significant and long-lasting impact on cassava yield in Nigeria. Interestingly, of all the climatic variables and gases studied, methane was identified as the greenhouse gas with the greatest long-term detrimental effect on cassava yield (Anyaegbu et al. 2022; Tofa et al. 2021). Especially in Lagos, the adverse effects of climate change include lower yields, reduced soil fertility, restricted water resources, increased rates of soil erosion, and the proliferation of pests, factors that threaten food security (Tajudeen et al. 2022).

In Burkina Faso, under different climatic conditions, including periods of drought, cold days, cold nights, the average daily number of wet days, and rainfall intensity, both favorable and unfavorable effects on maize, cowpea, millet, and sorghum yields over the period from 1961 to 2020 have produced (Sanou et al. 2023). Furthermore, it was found that climate change (increase in temperature pattern) could have variable effects on quinoa in Burkina Faso, favoring or hindering its growth depending on decisions taken at the farm level, such as when to plant and which crops to choose. For example, quinoa yields could potentially improve, particularly when the crop is irrigated and planted in November or December. By 2075, improvements in quinoa yields of around 14 to 33% have been projected in different agroclimatic zones, with the highest increase of 33% occurring in the Sudanian zone of the country under the RCP 8.5 scenario estimations (Alvar-Beltrán et al. 2021).

Agricultural crop production is predicted to decrease to less than 50 kg per capita by 2050 due to climate change, indicating a potential food shortage in the West African region (Defrance et al. 2020). At 1.5 °C, 2 °C and 3 °C, the research predicts spatial changes in crop suitability in West Africa, with suitability of legume and cereal crops extending into the central zone of the southern Sahel and the central zone of Guinea-Savannah, while root and tuber crops show reduced suitability south of 14 °C north latitude. In fact, climate trends have a significant impact on crop yields in the Sahelian zone of Gambia. While the Standardized Precipitation and Evapotranspiration Index has a positive relationship, temperatures have a negative and the combined effect of the indexes and temperatures resulted in the yield decline (Jabbi et al. 2021).

In Northern Africa, according to Amiri et al. (2021) simulations, cereal production in Morocco is projected to decrease due to temperature rise and rainfall variability, leading to the reduction of cereal yield and potential food insecurity for the growing population in 2024 and 2034. In contrast, a temperature increase over the next 51 years would have a positive impact on the potential yields and biomass of the two durum wheat cultivars 'Salim' and 'Karim' in the Nebeur/Tunisia region (Ayed et al. 2021). According to the findings of Beltran-Peña and D'Odorico (2022), if the climate temperature increases by 3 °C for example, Africa's total food production will only be enough to feed 1.35 billion people. This means that there will be a food deficit of 2.15 billion people, which is much higher than the projected population of 3.5 billion showing the degree of future climate and food challenges. In Africa in general and especially in northern Africa, rising temperatures hurt agricultural total factor productivity growth inducing the disturbance of the food system and further food insecurity (Bernard et al. 2023). Furthermore, Gamal et al. (2021) assess the impact of global warming levels of 1.5 °C and 2 °C on maize and wheat yields in Egypt. The results show that in a 1.5 °C warming scenario, wheat yields can increase by around 5%, but this positive effect diminishes when warming reaches 2 °C; while for maize, the effects are uncertain. Additionally, barley (22.7%), maize (48%), and wheat (10%) yields are expected to decrease at high altitudes. Similar results for wheat yields are found in Algeria. The wheat yields are expected to rise compared to the baseline period (1981–2010) in two regions of Algeria in different climate scenarios (Kourat et al. 2021).

Low rainfall and frequent droughts are likely to increase the impact of climate change on food production in South Africa, leading to future food insecurity. A downward trend in yield for future climate projections from RCP2.6 to RCP8.5 indicates that the potential impacts of higher temperatures and reduced rainfall in the projected future climate will lead to a marginal decline in wheat yield in the Eastern Free State of South Africa (Ajilogba and Walker 2023). Maize production will fall by 10–16% because of the climatic impacts forecast for the northeastern part of the country (Cammarano et al. 2020) and by 23.8% in the Eastern Cape (Choruma et al. 2022). Meanwhile, a positive correlation was found between drought and wheat yield losses, particularly in the western coastal province of South Africa (Nxumalo et al. 2022).

Some studies considering global Africa such as the one of Stuch et al. (2021) emphasize the major risks that climate change poses to food security. In Sub-Saharan Africa, especially in Central Africa, over 89% of harvested areas are expected to experience a decline in maize yields, leading to greater variability in yields. While 23% of harvested areas are still experiencing declines in tropical cereal yields, which are relatively more resilient, 37% of maize areas and 46% of tropical cereal areas are expected to experience a decline in food stability (Stuch et al. 2021). Other estimations under the RCP8.5 scenario by 2100 indicate that rising temperatures and reduced rainfall will make large parts of Sub-Saharan Africa unsuitable for main staple crops (maize, cassava, and soya). While soya is resilient to rising temperatures, maize and cassava are less adapted, particularly if the sensitivity to extreme temperatures is considered (Chapman et al. 2020), showing different impacts of climate change on crop production and eventually on food security.

3.2.2 Water resources

Water is a very dependent and important natural resource in agricultural activities especially in African countries where agriculture is essentially rainfed. However, changing rainfall patterns and rising temperatures affect water availability for agricultural activities development in the whole of Africa. In a region as vulnerable to climate change as West Africa, it is essential to have a reliable understanding of current water conditions and to be able to project the components of the water balance into the future for the development of appropriate adaptation strategies in agriculture. Using downscaled projections from the Rossby Centre Regional Atmospheric Climate Model (RCA4), the twenty-first-century water balance forecast for West Africa at global warming levels of 2° and 3 °C scenarios shows that precipitation is likely to increase in the southwest oceanic zone of the region, while other areas are expected to become drier at 2 °C and more intense at 3 °C. Runoff would also increase over the ocean, the Sahara, and part of the Sahel, and decrease over the savannah and the Guinean coast at 2 °C (Adeniyi 2021) due to climate change consequences like changes in temperature and precipitation patterns. These inconsistent and unpredictable temperatures and rainfall can negatively impact crop production in African countries, especially in coastal regions. The study carried out by Allani et al. (2020) on the impact of future climate change on water supply and demand in the Nebhana dam system in Tunisia points to an average increase in annual evapotranspiration of 6.1%, a decline in annual precipitation of 11.4%, leading to a 24% drop in inflow. In addition, the projection of crop growth cycles, particularly for wheat and citrus fruits shows a decrease of these crops by 5.4% and 31% respectively due to water scarcity. The same trend is observed for crop water requirements. Consequently, the study highlights the possible exacerbation of water supply challenges unless better planning of water surface use is implemented in response to climate change (Allani et al. 2020).

A calibrated and validated soil and water assessment tool was used to study the impact of climate change on water resources like surface runoff, lateral flow, water production, evapotranspiration, and sediment production in the Gilgel Gibe 1 catchment in Ethiopia. Results show that surface runoff and sediment production are expected to increase from August to December in RCP4.5 and from August to February in RCP8.5 (Demissie 2023). Durodola and Mourad (2020) investigated soybean crop water requirement, water productivity, and yields in the Ogun-Ona river basin in Nigeria. They found that between the period 1986 and 2015, water requirements and soybean yields were increasing, while crop water productivity was increasing. For the period from 2021 to 2099 crop water requirements are expected to fluctuate and depend on precipitation patterns. Nonetheless, they suggested that high levels of carbon dioxide (CO_2) fertilization should increase soybean crop yields by 40% under the projection of the RCP 8.5 scenario. On the other hand, a scenario predicts decreased streamflow in the Melka Kuntrie subbasin, exacerbating existing water shortages for agriculture, particularly in the minor rainy season (Getahun et al. 2020).

Research predicts a decrease in rainfall trends, coupled with an increase in temperature, leading to a 10.4% increase in annual evapotranspiration in the upper Blue Nile basin (Takele et al. 2022). In the Middle-Manyame sub-catchment in Zimbabwe, crop yields are estimated to increase significantly under different climate scenarios related to water availability. These yield improvements vary from 22 to 54%, while crop water usage for it is expected to decrease, resulting in a reduction in the blue water footprint of 19 to 38% (Govere et al. 2022). The impact of climate change is likely to decrease significantly river flows by 2100, with potential consequences for agriculture, and water availability for human and ecological systems in the Congo River Basin (Karam et al. 2023). Crop water productivity is forecasted to decrease by 11.6% in 2050 and 19% in 2100 in the Middle Egypt region due to increased greenhouse gas emissions (Mostafa et al. 2021a, b).

3.2.3 Livestock and pastoralism

Livestock farming is a farming sub-sector that generates income and livelihoods for around a third of Africa's population and contributes between 30 and 50% of agricultural GDP (Bogale and Erena 2022). Climate change also affects livestock production and pastoral communities in Africa. Changing climatic conditions can lead to reduced forage availability, water stress, increased livestock diseases, and changes in livestock heat stress, affecting the livelihoods of millions of pastoralists. However, the impact of climate change on domestic livestock is pronounced through heat stress. High temperatures, exceeding an animal's thermoneutral zone, can have a negative influence on livestock weight, mortality, performance, milk production, and reproduction, which can compromise animal welfare (Thornton et al. 2022; Ogundeji et al. 2021).

Previous studies have shown that temperature increases, and humidity induced by climate change are likely to affect heat stress and, consequently, harm livestock production in Africa (e.g. Rahimi et al. 2020, 2021). It is predicted by Brouillet and Sultan (2023) that many parts of West Africa will face a minimum of 5 to 6 stressors simultaneously by the 2030s, including increased severe heat stress and higher exposure to flooding. This scenario could potentially expose around 30% of the region's current livestock to these factors combined, making sheep and goats the most vulnerable species. The author of Rahimi et al. (2020) pointed out that cattle production is undermined by heat stress conditions in West Africa. Their estimates show that periods of severe heat stress are expected to increase from 4 to 7 days by 2021–2050 to 70 days by 2071–2100, leading to significant decreases in livestock's productive and reproductive performance, particularly in the southern half of West Africa. Later the author of Rahimi et al. (2021) supported these last findings by conducting the same experience in East Africa. Under RCP 4.5 and 8.5 projections from 2071 to 2100, the dangerous frequency of heat stress events will increase and severely negatively impact future livestock production in East Africa, particularly for pigs and poultry (Rahimi et al. 2021).

In the study performed by Ekine-Dzivenu et al. (2020), it was found that heat stress had an impact on milk production in small dairy herds in Tanzania. Using the temperature-humidity index (THI) based on climatic data, the results reveal that heat stress significantly reduces milk production by 4.16 to 14.42% within THI groups. Similar outcomes were also reported by the authors of Ogundeji et al. (2021), indicating that for the semi-arid regions of the Free State (Bloemfontein, Bothaville, and Bethlehem) in South Africa, heat stress significantly decreases farmers' milk production in summer conditions when the temperature exceeds 25 °C. Projections with a THI threshold of 65, suggested that the three regions would lose approximately daily ZAR 1.27 per cow, leading to an annual loss of ZAR 64,897, supposing the average cow's sample is 140.

On the other hand, pastoralists along the Ethiopia-Kenya-Somalia border have experienced a period of extreme drought. Between 1990 and 2003, they lost almost 80% of their livestock (Bogale and Erena 2022). The results of the study carried out by Ngarava et al. (2021) in the local municipality of Port St. Johns indicate that flooding caused by climate change (especially excessive rainfall) has led to a reduction in the productivity of sheep, poultry, pig, goat, and cattle farmers, as well as a reduction in the availability of meat and an increase in prices. South Africa suffered a severe drought in 2015–2016, particularly in the Msinga region of KwaZulu-Natal, which accounts for the livestock of some 3000 households. The breeders of bovine have lost 43% of their animals, against 29% for the goats during the phenomenon. These results show that the larger herds are more vulnerable to flooding than the smaller ones. However, over the last 20 years' estimations, the main effects of the trend towards higher temperatures and lower rainfall on livestock production in south-west Ethiopia were reductions in feed supply and quality, water availability, milk production, and animal fertility, as well as an increase in the calving intervals, the frequency of breeding per conception and the incidence of animal diseases and parasites (Abazinab et al., 2022). According to Goma and Phillips (2022), Egypt is currently facing heat-stressed summer conditions for livestock. Climate change projections suggest that these conditions will worsen this century and are likely to be severe, leading to a reduction in food security. Livestock production can be improved through climate change adaptation and mitigation measures based on geography and livestock systems.

There has been little detailed work in the last years that assesses how livestock populations are affected by climate change in Africa. However, climate is one of the main factors influencing agricultural sector productivity and water availability, both directly and indirectly, as it is related to natural physiological functions. It is therefore important to understand the different strategies used by farmers to adapt and mitigate the negative impact of climate change developed in the next results section.

3.3 Adaptation strategies and their effectiveness in African agriculture

The magnitude and pervasiveness of the impacts of climate change on agricultural systems create a compelling need to ensure the full integration of these impacts into agricultural planning, investments, and programs in Africa. It is in the search for solutions to this need that sustainable agriculture practices such as Climate-Smart Agricultural (CSA) were revolutionized by FAO in 2010. The literature recognizes the potential of sustainable agriculture as one of the most important approaches to combat different shocks such as climate change consequences and ensuring food security and livelihoods for rural households in Africa (Abdallah et al. 2021). Many techniques have been and are being used in the same country and from region to region to find better alternatives to soil degradation and poverty, water scarcity, and extreme temperatures. Among them are crop diversification and new crop varieties, climate-smart agriculture, water management, and livestock management techniques. These adaptation strategies are generally applied not solely but in combination.

3.3.1 Crop diversification and related strategies

West African farming communities have a long history of adopting a variety of survival and adaptation strategies in response to periods of climate change and risk. Such strategies have been mainly driven by existing local knowledge systems and a collective understanding of the factors behind extreme weather conditions (Adaawen 2021). Farmers in Africa have been adopting crop diversification strategies to enhance resilience to climate variability. Planting multiple crop varieties with different maturation times and drought tolerance helps spread risks and increase overall productivity.

In particular, crop rotation and row planting, drought-tolerant crop varieties, indigenous knowledge, irrigation, migration, an adaptation of planting calendars, crop diversification, mixed farming, and sustainable land management are all key adaptation strategies for sustainable food production in northern Ghana, resulting in greater maize yields and improved technical efficiency for maize farmers (Adzawla and Alhassan 2021; Antwi-Agyei and Nyantakyi-Frimpong 2021). However, women farmers have especially targeted altering their planting dates in response to drought, drained and moved away from flood-prone areas in response to flooding, and established fire belts around their farms to prevent damage from bushfires (Owusu and Yiridomoh 2021). Maize is a major staple and plays an essential role in food and nutrition security in Sub-Saharan Africa (SSA). Especially, maize is the most widely grown cereal crop and an important staple food that is grown in all the agricultural zones of Ghana. To cope with the impacts of climate change, Aidoo et al. (2021) identified 17 adaptation strategies adopted by maize farmers in Ghana. However, the most commonly adopted strategies were changing planting dates, crop diversification, use of resistant crop varieties, and radio monitoring of weather forecasts. To tackle the impact of climate variability, more than 82% of yam farmers in the Ejura Sekyedumase

Municipality, Ghana, have used key adaptation practices, notably altering the yam planting period, planting early maturing yam seeds and varieties, and intercropping yam with some other crops (Baffour-Ata et al. 2023). Among the main adaptation strategies are altering planting dates, diversification into off-farm activities, growing improved cocoa varieties, diversifying crops, and planting trees by cocoa farmers in the Wassa East district of the country (Kosoe and Ahmed 2022).

Over 80% of farmers in north-east Burundi have adapted to climate change by modifying crops, and fertilizers and planting shade trees (Batungwanayo et al. 2023). For example, for 91.47% of farmers in Central Ethiopia, improving crop varieties and input intensity, crop diversification, adjusting planting dates, soil, and water conservation practices, and changing crop type were used as options to adapt to climate risks (Addis and Abirdew 2021). In northwest Ethiopia, crop planting dates have been adjusted, crops have been diversified, terraced, trees planted, drought-tolerant varieties grown, and non-agricultural activities carried out (Likinaw et al. 2022). Nevertheless, in southern Ethiopia, farmers have tried to apply a number of adaptation practices, among them soil and water conservation through organic measures, use of improved crop varieties, terracing, agroforestry, use of improved breeds, cutting and transport systems, managed grazing and incorporation of residues (Belay et al. 2022) and improved soil amendment practices, varying planting or harvesting schedules, and crop rotation (Sedebo et al. 2021). For example, the Dandaa wheat new crop variety performs well under late sowing, recording yield increases of between 140 and 148 kg/ha at mid- and end-century under RCP4.5, meanwhile the wheat cultivar Kakaba shows greater potential for adaptation, with yield increases of up to 142 and 170 kg/ha at mid- and end-century under RCP8.5 (Demelash et al. 2021).

Farmers are using adaptation strategies such as organic fertilizers, changing planting dates, and growing short-life maize varieties in southern Mali to boost maize productivity and food security in the context of climate change impacts (Diallo et al. 2020). Data collected from 540 farmers in six regions of Kenya show that 55% plant drought-tolerant crop varieties, 34% grow diversified crops, 22% grow early-maturing crops and 18% diversify their income sources as their main coping strategies (Gebre et al. 2023). Farmers in western Kenya are implementing various adaptation strategies such as altering planting dates, diversifying crops, and using drought-tolerant crop varieties to combat the impact of climate change (Kogo et al. 2022). Meanwhile, in Niger, more than 50% of households are using cropping and income diversification and changes in planting periods as coping strategies. Farmers who adopt these practices are more likely to improve their household income and food security (Zakari et al. 2022). Crop diversification is an essential coping strategy to enhance the resilience of both agricultural production and food systems to climate-related risks. The level of crop diversification, reflecting the degree of climate risk mitigation, is influenced by the ability of smallholder farmers to efficiently allocate the resources at their disposal (Awiti et al. 2022).

3.3.2 Climate-smart agriculture

Climate-smart agriculture (CSA) offers a unique opportunity to adapt to the effects of climate change while mitigating greenhouse gas emissions from agricultural activities and increasing productivity at the same time (Abegunde et al. 2020). Climate-smart agriculture practices, such as conservation agriculture, agroforestry, and precision farming, have gained traction in recent years. These practices promote sustainable land use, water conservation, and efficient resource management. The use of organic fertilizers, crop rotation, and crop diversification are the most popular climate-smart farming practices among farmers sampled in the King Cetshwayo District Municipality in South Africa (Abegunde et al. 2020).

In rural Malawi, farmers have been able to adopt ex ante and ex post adaptation strategies to cope with climate shocks. On the one hand, farmers have adopted more on-farm labor, drought-tolerant varieties, early planting, and intercropping as their main ex ante adaptation strategies. On the other hand, the adoption of drought- and disease-tolerant crops, crop diversification, earlier planting, more on-farm labor, and changes in dietary habits were the main ex-post adaptation strategies to climate shocks (Abid et al. 2020). A positive correlation was found between overall yield and the adoption of organic fertilizers, intercropping with legumes, and the use of hybrid seeds practices in Malawi (Maggio and Asfaw 2020). CSA including land management based on minimum tillage, incorporation of crop residues, use of cover crops, and inclusion of legumes in Eastern Africa (Malawi and Zambia), have relatively higher economic returns. Agroforestry, in contrast, offers lower economic returns but the greatest potential for reducing emissions (Branca et al. 2021). Also, other CSA practices, comprising conservation agriculture, maize-pigeon intercropping, and Mbeya fertilization, have improved soil quality, increased maize yields, and sequestered soil carbon, making a contribution to climate change mitigation in Malawi (Nyagumbo et al. 2022).

It is said that CSA practices have the potential to lower or zero greenhouse gas emissions and to further boost farm revenue and profitability. For example, the study by Agbenyo et al. (2022) found that the adoption of irrigation and crop insurance practices increased cocoa farmers' household income by 8.6% and 11.1% respectively. They conclude that crop insurance is among the most cost-effective and climate-intelligent practices that affect farmers' incomes positively in Ghana. Evidence from Ghana, Mali, and Nigeria also shows a positive link between the adoption of CSA and increased crop yields, resulting in increased food security, particularly when improved crop varieties and several CSA practices are combined (Tabe-Ojong et al. 2023). Integrating agroforestry into CSA measures would potentially improve the agricultural sector productivity of smallholders affected by climate change (Amadu et al. 2020a, b). CSA among smallholder sorghum farmers in Busia County/Kenya includes conservation agriculture, agroforestry, water conservation, use of tolerant varieties and breeds, and use of risk insurance. However, despite the proven benefits, adoption of these practices remains low in the country (Atsiaya et al. 2023).

The use of effective soil and water conservation (SWC) practices (e.g. tied ridges and conventional tillage) may also be a valuable strategy for minimizing potential losses due to climate change in the arid areas of the eastern Democratic Republic of the Congo (DRC) (Bagula et al. 2022). However, in the Yangambi landscape of the country, only 12% of farmers practice crop rotation, fallowing, fertilizers, and biopesticides (Mangaza et al. 2021). Biophysical soil and water conservation technologies, agroforestry, small-scale irrigation, livelihood diversification, and the cultivation of high-yielding, drought-resistant varieties are being implemented by farmers in Basona Worena district, North Shewa zone, Ethiopia, as adaptation strategies to climate change and variability (Hilemelekot et al. 2021). Only 22% of farmers in the drier areas of the Arsi Zone of the Oromia Regional State have adopted sustainable practices such as early-maturing wheat varieties and soil and water conservation (Belete et al. 2022).

The combination of Zai and mulch on crop yield practices seems to be a better option for improving crop productivity in the context of climate change in southwest Niger (Issoufou et al. 2020). The research by Traore et al. (2022) revealed that transplanting combined with NPK fertilizers was a promising strategy for adapting pearl millet cultivation to climate change and variability in the country. Stove-grown biochar is an adaptation strategy that can reduce greenhouse gas emissions from small farms in Africa and increase agricultural yield (Sundberg et al. 2020; Koné and Galiegue 2023). To deal with the negative effects of climatic variations in the Sudanian zone of Côte d'Ivoire, farmers have implemented a series of adaptation strategies, involving the application of manure, agroforestry, changes in planting dates, and the planting of new crops (Timité et al. 2022). The application of 150 kg of nitrogen combined with 30 kg of phosphorus per hectare as an adaptation to climate change mitigates the impact of climate change on maize yield loss and improves cereal yields in some areas of Nigeria (Tofa et al. 2023). The application of CSA technologies such as edge fixation, micro-dosing, intercropping, Zai pits, and variety-adapted treatments has led to an increase in millet yield of 51%, 35%, 23%, 69%, and 27% respectively, and has secured food security for smallholder households in Mali (Traore et al. 2021).

CSA practices increase climate change adaptation capacity, increase the total amount of nitrogen, phosphorus, and potassium in the soil, independently of the type of soil use or soil deepness (Recha et al. 2022), reduce GHG emission of farms, increase productivity and enhance food security (Teklu et al. 2022). Sustainable land management offers effective climate change adaptation practices that build resilience while simultaneously helping to secure production. These practices are particularly valuable for land users in sub-Saharan Africa that depend on rain-fed agriculture (Critchley et al. 2023). The combined application of strategies remains more effective than a single application. For example, the research found that the adoption by rural African households of practices such as no-till, intercropping, residue incorporation, and the use of animal manure increases farm income and food security compared with the adoption of a single practice or non-adoption (Abdallah et al. 2021).

3.3.3 Water management

The review has highlighted the importance of water management strategies, such as rainwater harvesting, irrigation, and water-efficient practices, in mitigating the impact of water scarcity on agricultural productivity. Effective water management practices, including rainwater harvesting, small-scale irrigation, and water-efficient technologies, are being implemented to cope with water scarcity and variability across African countries. Irrigation has generally positive impacts on farm incomes, employment, consumption, food security, and non-farm activities, all crucial for successful small-scale agriculture transformation in Ghana (Akudugu et al. 2021). Evidence suggests that farmers who use a combination of agricultural and non-agricultural strategies to cope with the effects of flooding in Ghana's Upper East Region have seen their food security situation improve and have recovered more quickly from the shocks caused by flooding than those who do not (Alhassan 2020). Agricultural and water management practices adopted by tomato growers in Ghana include crop rotation, fertilization, and water reservoirs to respond to climatic variations (Benabderrazik et al. 2022). Farmers in Ghana have significantly increased the adoption of water management and multiple cropping practices by 6.8% and 5.6%, respectively, through the use of weather and climate information services (Djido et al. 2021).

Alavaisha et al. (2022) found that implementing alternate wetting and drying with a rice intensification system for a single cropping season is a viable method to maintain high levels of soil organic carbon and total nitrogen, while also potentially increasing crop production and reducing water usage in Tanzania's Kilombero Valley. The government recommends irrigation and drought-tolerant seed strategies to help smallholders in southern

Tanzania increase crop yields and adapt to climate change. However, Ines 2021 found that irrigation did not significantly contribute to increased paddy production in the region. Other adaptation strategies found in Tanzania are crop and livestock diversity, the use of chemical fertilizers, minimum tillage, and agroforestry (Kurgat et al. 2020; Osewe et al. 2020).

Burkina Faso farmers have a long history of adaptation to climate change. In this country, their adaptation strategies are based on traditional knowledge and experimental or market-oriented approaches. Various adaptation practices are adopted by farmers depending on the climatic, societal, and economic context. They include soil and water management practices. These strategies include half-moon farming, crop rotation, crop association, stone bunds, drip irrigation, minimum tillage, agroforestry, and many others (Alvar-Beltrán et al. 2020). In the Bafuliru region of the Easter DRC, several strategies including increased irrigation practices and use of inputs, more soil conservation measures, and more income diversification activities have been applied by farmers to adapt to climate change (Amani et al. 2022). Increased nitrogen fertilizer is beneficial in combination with higher CO_2 levels for wheat production in areas with adequate rainfall, while irrigation is necessary for low-rainfall regions (Araya et al. 2020).

In the province of Sud-Kivu, farmers are using various adaptation strategies to address the challenges of climate change. These include drainage, mulching, the application of manure as well and crop diversification, which help to handle flooding, maintain soil fertility, and minimize crop losses. In addition, because of the land shortage, a major number of women farmers (75%) and men farmers (60%) are actively seeking new land in mountainous regions and renting additional plots in marshes or other locations (Arsene et al. 2021). The principal water stress adaptation strategies include improving soil moisture conservation, building small reservoirs, water billing and trading, and setting clear priorities for water use among small-scale irrigators in Zimbabwe (Mwadzingeni et al. 2023). In response to water stress, soil degradation, and nutrient depletion, most potato producers have resorted to supplementary irrigation, and mineral and organic fertilizers in the highlands of eastern Ethiopia (Woldeselassie et al. 2021).

3.3.4 Livestock management

Adaptation strategies found for livestock management may include improved animal husbandry practices, early warning systems for disease outbreaks, and diversification of income sources for pastoralists. For example, to address the impacts of climate change on livestock production and productivity, diversifying mixed crop-livestock systems and diversifying livestock species, feed conservation methods, reducing herd sizes, water harvesting techniques, provision of supplementary feeds, and forage production are the common adaptation strategies practiced by the livestock farmers in the Gera district, southwest Ethiopia (Abazinab et al. 2022). Assane and Waounde (2023)study results show that 73.7% of the 410 pastoral households surveyed in Senegal use at least one coping strategy, which includes stockpiling feed, increased mobility, changes in water management, diversification of activities, and adjustments in herd composition. In addition, the research suggests that coping decisions among pastoral households may be made jointly, with those with mobility relying primarily on it as their only coping strategy, while those without mobility adopt multiple strategies.

Improved access to resources, especially land, and the implementation of effective policies can strengthen the resilience of 79% of small-scale livestock farmers to the harmful effects of agricultural drought in the Northern Cape province of South Africa (Bahta and Myeki 2022). Dairy farmers in Benin, Burkina Faso, and Niger practice transhumance in wetlands and use manure and plants to adapt to climate change and improve milk production. Mali's dairy farmers, meanwhile, focus on fodder production and conservation, milk sales, and pasteurization to adapt to climate change (Montcho et al. 2022). The drought impact of 2014–2016 in the local municipality of Greater Letaba in South Africa, combined with the loss of animals, prompted 37% of small-scale livestock farmers to reduce their herds, 25% to buy extra feed for their animals and 6% to drill wells as resilience strategies (Rakgwale and Oguttu 2020).

3.4 Discussion and perspectives

The systematic review highlights the significant impact of climate change on agriculture in Africa and the diversity of adaptation strategies employed by farmers, policymakers, and communities as well as their effectiveness. Results show that the effect of climate change on yields varies significantly between regions, farms, and from year to year depending on climate variables variability. The main impacts are yield losses and sometimes gains depending on the crop and region. Climate change also has many consequences for livestock in Africa including reduced access to feed and water, heat stress, biodiversity changes, disease shifts, and increased vulnerability to livelihoods. These effects decrease food security, purchasing power, and resilience to climate shock.

Climate-smart agriculture (CSA) plays an important role in African countries in achieving rural development and environmental sustainability objectives (Amadu et al. 2020a, b). While several successful sustainable adaptation initiatives have been identified, challenges remain in implementing and scaling up these strategies, particularly in resource-constrained regions. The results of numerous studies also have shown that adopting sustainable practices as a package rather than as a single practice enables farm households to generate significant benefits in terms of well-being than a single practice. Some findings suggest that the world should focus more on enhancing adaptive capacity to moderate potential damage and on coping with the consequences of climate change.

Many gaps and challenges exist in these selected research results. As projections vary considerably from one study area to another, it will be difficult to predict with any precision or assurance what the future might bring. There is a lack of clear understanding of the various CSA practices that can be implemented at the farm level hinders the uptake of CSA in developing countries. There is a gap in research on the impact of climate change on water resources and water resource management as well as the impact analysis on livestock and livestock management. Also, studies did not focus on the impact of climate change on the different components of food security including food availability, accessibility, stability, and utilization.

The international community's efforts to promote Climate-Smart Agriculture (CSA), and its implementation still remain low in many areas. Adaptation to climate change has many constraints such as material limits related to access to inputs, new technologies, market access, access to information and climate services and culture linked to less interest in farming, and less capacity for smallholders to organize into farmers' cooperative groups. The lack of knowledge of climate change's real consequences as well as the adoption of effective adaptation strategies by crops are among other constraints to a sustainable fight against climate change in agriculture. Developing relevant decision-support tools for policymakers to support large-scale implementation of climate-smart agriculture in the Global

South is challenging given the great diversity in biophysical, socio-technical, and organizational conditions.

There is a lack of gender aspect integration in agriculture adaptation practices. Practices, as well as their constraints and effectiveness, may differ from women to men. As women are the most vulnerable, gender-differentiated behavioral and economic factors to design effective climate policy interventions are necessary. Capacity building among farmers is a key to applying effective adaptation strategies by considering women's leadership which is important in the adoption of sustainable adaptation strategies. Demographic characteristics and social networks may also influence agricultural practices. So, agricultural advisory and extension services should target addressing specific gender needs among farm households to improve resilience to climate variability and change in peri-urban spaces. Overall, practical implications policies and strategies to promote CSA should consider local farmers' perceptions of climate change and consider first the adequacy of CSA practices for the specific conditions of the target area before its promotion. To do so, a framework for CSA should be proposed for each crop and region's climate conditions.

4 Conclusion

This article provided a comprehensive systematic review of the research conducted on the impact of climate change on agriculture in Africa and the adaptation strategies employed to address these challenges in the last four years. In total, 125 suitable articles from different regions of Africa including Northern Africa, Eastern Africa, Middle Africa, Southern Africa, and Western Africa were included in the results. The findings emphasized the difference in climate change impact across regions and the implemented climate-resilient and sustainable agricultural practices to ensure food security and livelihoods in the face of a changing climate as well as the urgency in considering adequate strategies to cope with climate change consequences in agriculture. Climate change has a different impact on crop productivity and the impact could be negative as well as positive depending on the crop time, the soil type, the region, and the magnitude of climate adverse. Most results showed a negative relation between crop yield and temperature, while a negative correlation exists with precipitation. This highlights the need for agricultural diversification and the development of livelihood opportunities to cope with climate variability. Despite the amount of research, there is a lack of research in many regions, especially on the impact of climate change on livestock, livestock management strategies, water and water management techniques. An in-depth understanding of the potential implications of climate change is required to guide decision-makers when developing adaptation strategies and designing infrastructure suitable for future conditions. The review contributed valuable insights for policymakers, researchers, and stakeholders in advancing climate change adaptation efforts in African agriculture. The study recommended more research and the integration of gender aspects in the implementation of climate change strategies application and effectiveness assessment and the consideration of different food security components while analyzing climate change's impact on food security. These results can be useful for climate change consequences management actions development throughout different regions.

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Data availability All data is included in the paper.

Declarations

Conflict of interest The authors declare no competing interests.

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