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Review article

The socioeconomic impact of climate change in developing countries over the next decades: A literature survey

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ABSTRACT

Extreme weather events, rising temperatures, and shifting rainfall patterns pose significant threats to developing countries with fragile social, economic, and political structures. While research has intensified on socioeconomic impacts of climate change, existing survey studies exhibit substantial scope variations and seldom concurrently analyze these impacts, hindering policy coordination. This study reviews literature on the broad spectrum of socioeconomic impacts of climate change to discern trends and underscore areas requiring additional attention. The survey unveils that, across various socioeconomic indicators, the most vulnerable groups bear a disproportionate burden of climate change, with long-term impacts forecasted to surpass medium-term effects. Adaptation and mitigation options are feasible but must be tailored to local contexts.

Declaration

This study was originally published as a Centre for Global Development (CDG) working paper in (https://www.cgdev.org/publication/socioeconomic-impact-climate-change-developing-countries-next-decades-review). There have also been several news articles published on this study in Bloomberg, the Conversation Africa, International Radio France (IRF), etc.

1. Introduction

Recent evidence indicates increasing trends in extreme weather events, warmer temperatures, and changing rainfall patterns [1]. The IPCC reports that Earth's average temperature increased by 1.09 °C from 2011 to 2020 compared to 1850–1900 levels and predicts a 50 % chance of reaching or exceeding 1.5 °C warming even with low greenhouse gas emissions [2]. Extreme weather events, once occurring every 10 years in the late 19th century, now occur 2.8 times per decade and could increase to 4.1 times per decade if global warming hits 1.5 °C [2]. This poses significant risks to environmental sustainability due to the interconnectedness of climate, biodiversity, ecosystems, and human societies. Rising extreme weather frequency and intensity are harming biodiversity and causing population collapses and local extinctions [3].

Various studies indicate climate change's extensive impacts on the economy [4–7], human health [8,9], water resources [10], food systems [11–14], economic growth [15–19], labor productivity [1], energy markets [20], and poverty [21]. Developing economies,

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with low adaptive capacities, face the most severe consequences [22–26]. Climate change threatens to undermine previous development gains and make achieving the United Nations Sustainable Development Goals (UN SDGs) unattainable in affected developing economies [26].

This growing concern has heightened research into the future socioeconomic impacts of climate change [27–29]. However, existing studies vary significantly in scope and rarely analyze these impacts simultaneously, complicating policy coordination [28–32]. Moreover, the lack of consensus on the relative and absolute scale of climate change impacts across sectors and development outcomes in the literature creates uncertainty in policy design and weakens efforts to address climate change [16,33–35].

Synthesizing evidence from previous studies helps to identify general impact patterns and research gaps. Existing literature reviews are often narrowly focused, missing the interconnected nature of climate change's socioeconomic impacts, which is crucial for effective policy coordination. For example, Tol [22] reviewed economic impacts and social costs, Han et al. [10] examined the water-food-energy nexus, Yalew et al. [36] reviewed climate change impacts on energy demand, Cronin et al. [37] reviewed climate change impact on energy supply, while Li et al. [38] and Roudier et al. [39] focused on energy use in built environments and crop impacts, respectively. This survey broadens the scope to include economic welfare, agricultural productivity, food security, health, energy, and water resources. I reviewed literature on the medium- (2030) to long-term (2050 and beyond) impacts of climate change, focusing on developing countries to identify trends and highlight areas needing further attention. Considering climate change impacts on various socioeconomic indicators is essential for developing comprehensive and well-coordinated climate change policies. I find that the most vulnerable groups are disproportionately affected, with long-term impacts being more severe than medium-term ones. Tailored adaptation and mitigation strategies are essential, especially for the most vulnerable countries, to address future climate change impacts effectively.

2. Method and data summary of the surveyed studies

2.1. Review type and scoping strategy

Various studies have explored the potential impacts of climate change on socioeconomic, environmental, and political factors in different contexts. This section sets the boundaries for the studies included in the review, aiming to identify trends and patterns in the literature, particularly from a developing economy perspective. By conducting a desk literature review, this study aims to establish the scope, trends, and patterns of existing evidence. Due to differing assumptions in climate change impact models, the study cautiously compares findings, focusing on general patterns and trends rather than direct comparisons.

The desk review followed several steps.

1. **Keyword Identification**: Two broad categories of keywords were used:
   - **Climate change indicators**: climate change, temperature, precipitation, carbon dioxide emissions, pollution.
   - **Socioeconomic factors**: economic growth, income, poverty, welfare, health, agricultural productivity, water resources, energy demand, energy supply, energy security.
2. **Search Process**: Each climate indicator was paired with each socioeconomic factor in searches. These initial searches were broad, without limitations on period or context, to assess the depth of existing research.
3. **Sorting Evidence**: The gathered evidence was sorted to focus on essential studies. Inclusion and exclusion criteria were then applied to narrow down the literature, aligning with the key research question. Table 1 outlines these criteria.

2.2. Nature of the study and data collection strategy

The review prioritized studies with a strong quantitative orientation to measure the future impact of climate change on socioeconomic indicators. However, qualitative studies were not disregarded if they made efforts to quantitatively measure the impact. Preference was given to quantitative or mixed-methods studies. A total of 139 studies from 79 publication outlets were surveyed, gathered from search engines like Scopus, Google Scholar, and the Web of Science database. Duplicate studies were removed, and additional data were collected from bibliographies, reports, books, working papers, and conference papers.

Table 1
Exclusion and inclusion criteria for selecting the database.

Inclusion Criteria	
IR1:	The context of the study should at least include one developing country
IR2	The study should adopt either a strictly quantitative or mixed approach in the assessment of the impact of climate change.
IR3	The study makes medium- to long-term predictions of climate change impacts
IR4	The outcome of the examination should include one of the socioeconomic indicators identified earlier in this study.
IR5	The study contains a clear description of the methods and data
Exclusion Criteria	
EC1	The study is inaccessible either at the time of review or due to subscription requirements.
EC1	The study adopts a strictly qualitative approach
ECI	The study was published in a predatory journal or suspicious outlet

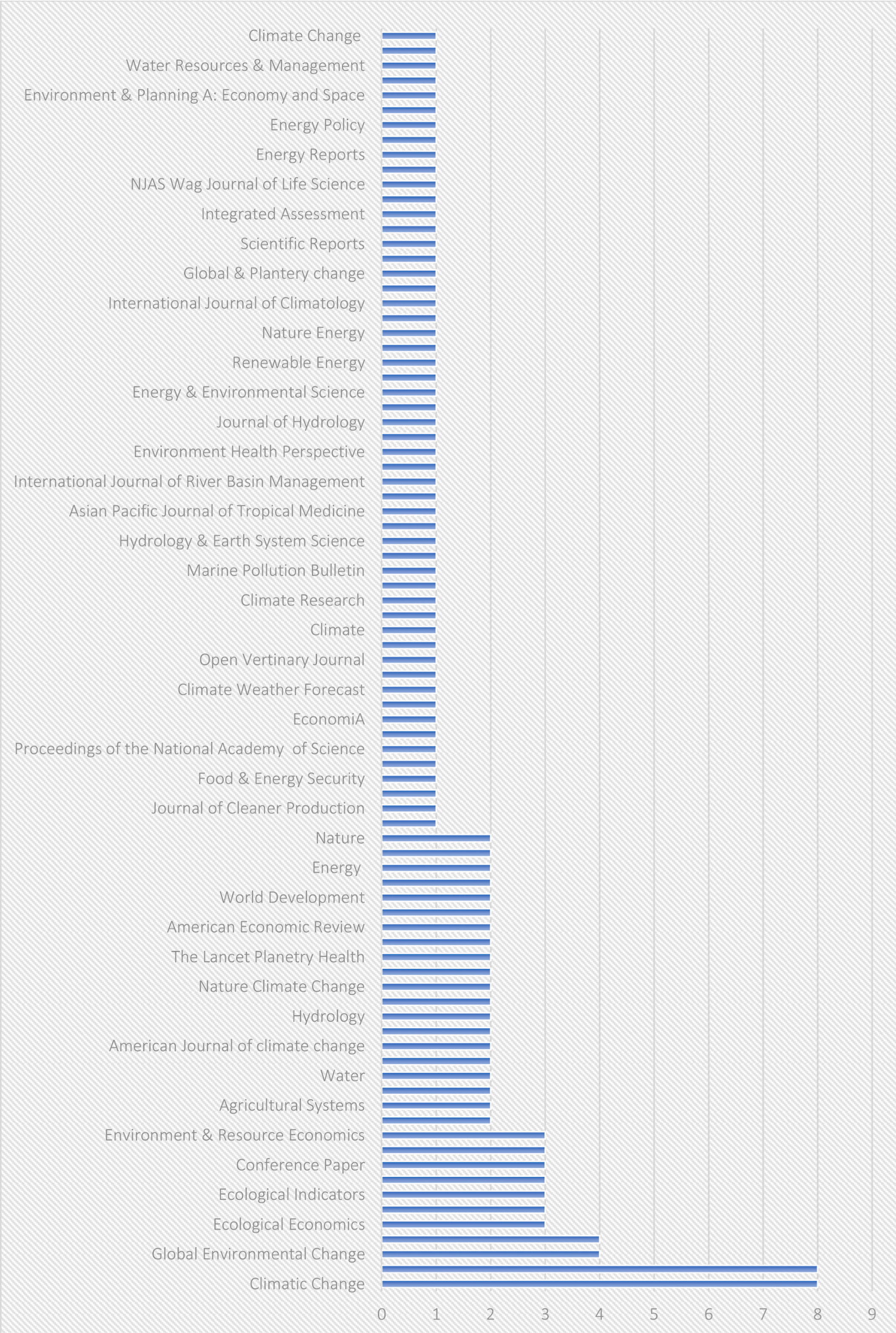

Fig. 1. Distribution of studies by publication outlet.
Source: Author's own construction.

2.3. Summary of the data

The surveyed studies comprise mainly journal articles, along with conference papers, reports, books, book chapters, and working papers. No single publication outlet emerged as a clear leader, although journals like Climatic Change, Global Environmental Change, and Science of the Total Environment published a slightly higher number of studies compared to others (see Fig. 1). The distribution of publication dates shows a skew towards recent years, with the majority of papers published after 2017. The highest numbers of publications were recorded in 2020 and 2022, followed by 2021, 2018, and 2019 (see Fig. 2). These statistics indicate a renewed interest in climate-related studies in recent times.

The review includes studies categorized by context type: grouped and country-specific. Most studies (85) utilized group-level data, while the rest used country-level data (see Fig. 3 Of the 85 group data studies, 49 used global data, while others used regional- and subregional-level data (see Fig. 4). The distribution of studies by specific country focus indicates a concentration on certain regions: India (8 studies), China (7), and Ethiopia (4) were the most studied countries. Notably, the focus on climate change impacts is biased towards Asia and Africa, with 20 country-specific case studies from Africa and 34 from Asia out of a total of 54 (see Fig. 5). Overall, country-specific studies are underrepresented in the literature, indicating a need for more evidence to establish the heterogeneity of climate change's impact on socioeconomic indicators across different countries. This is particularly important for contextualizing local climate change policies.

The distribution of papers by theme indicates a predominant focus on the agricultural sector for assessing climate change impacts (see Fig. 6). Out of 139 reviewed studies, 47 assessed climate change's impact on agricultural productivity, primarily focusing on food security measures. This emphasis on agriculture may be due to developing economies' heavy reliance on the primary sector, making them highly susceptible to climate change impacts. Economy-wide assessment studies using GDP or other welfare measures account for the next largest group (36 studies), followed by the water and energy sectors with 17 and 19 studies, respectively. Studies on climate change's effects on health, hunger, undernourishment, and poverty total just 20, indicating an underrepresentation of these areas in the literature. Overall, more evidence is needed to build consensus on climate change impacts, particularly in underrepresented areas of developing economies.

3. Medium- to long-term impact of climate change in developing countries

3.1. Impact of climate change on economic growth and income

3.1.1. Global case studies

The relationship between the economy and the environment has been extensively studied, yet it remains ambiguous due to various factors such as context, temperature pattern variability, technological advancements, and countries' adaptive capacities, all of which significantly mediate this relationship. Since the early 1990s, when major concerns about the impact of climate change first arose, significant research has been conducted to assess the impact of climate change on economic output. Early studies such as Cline [40], Fankhauser [41,42], and Tol [43] evaluated both tangible and intangible damages of climate change based on literature, extrapolation, and guesswork, particularly if atmospheric carbon dioxide emissions double. While these studies generally agreed on the negative impact of climate change on economic output, they differed in the magnitude of that impact. Debates persist on whether the projected impact of climate change on economic outcomes is linear or nonlinear, introducing uncertainty in policy development.

It is now widely acknowledged that few countries will be immune to the adverse effects of climate change, although the impact on economies and the benefits from adaptation are unlikely to be uniform across economies and sectors. Studies have shown a nonlinear concave effect of climate change on economic growth, indicating that while additional global warming may stimulate growth in cooler areas, it will reduce growth in hotter regions. Research by Mendelsohn, Morrison et al. [27]; Mendelsohn, Schlesinger, and Williams [44]; Stern [45]; and the IPCC [7] has demonstrated that the impact of climate change on economic output varies across world economies. Developing economies are at the highest risk, while developed economies are more likely to experience gains. Using global data, studies by Burke et al. [32], Diffenbaugh and Burke [46], and Duan et al. [18] found that additional warming accelerates growth in cooler regions while impeding growth in warmer regions. However, a critical concern is the uncertainty surrounding the temperature threshold beyond which negative impacts of climate change will emerge (optimum temperature). The current literature estimates a median optimum temperature of 13.1 °C but suggests a 5–95 percent chance that it falls within the range of 9.7°C-16.8 °C [32]. Due to the majority of world GDP being generated in temperatures higher than the median optimum temperature, substantial uncertainty persists regarding the magnitude of climate change's impact.

In assessing the economic impact of climate change, various methods have been utilized in the literature, each with distinct strengths and weaknesses. For instance, Nordhaus [47] and Tol [43,48,49] employed the enumerative approach, relying on natural science studies to determine the physical effects of climate change. While this method yields physically realistic and easily interpretable results, concerns arise regarding extrapolation, including using economic values from other issues for climate concerns and extrapolating from a limited number of locations to the world. Extrapolations in assessing the impact of climate change on economic variables likely carry substantial error, as highlighted by Brouwer and Spaninks [50]. Therefore, predictions regarding the impact of climate change on economic variables may be subject to significant uncertainty. Statistical methods, on the other hand, use observational data to estimate climate change's effects on economic variables, allowing for the use of real-world observed data. However, these methods may struggle with attributing observed differences across locations to climate change and may overlook significant spatial variations in certain aspects of climate change, such as carbon dioxide fertilization and the direct effects of sea level rise.

At the global level, major studies quantifying the future impacts of climate change include Mendelsohn, Morrison et al. [27];

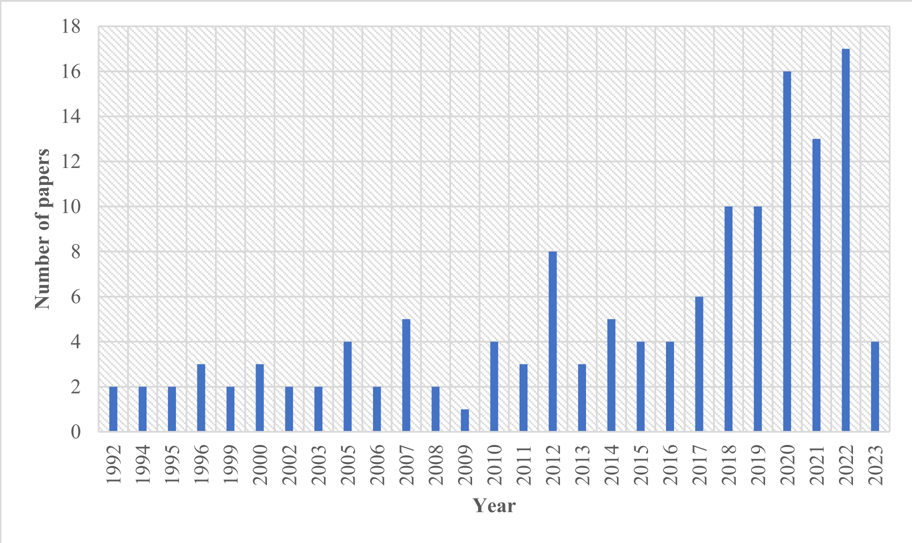

Fig. 2. Distribution of studies by year of publication.
Source: Author's own construction.

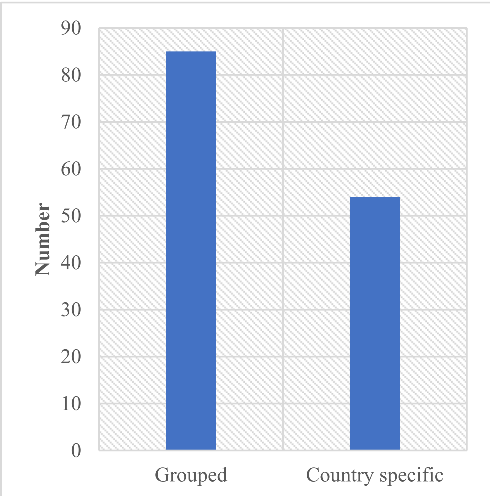

Fig. 3. Distribution of studies by context.
Source: Author's own construction.

Mendelsohn, Schlesinger, and Williams [44]; Stern [24,45]; Weitzman [51]; Nordhaus [29]; and Dietz and Stern [28]. Mendelsohn, Morrison et al. [27] projected a cumulative loss of 0.3 percent of GDP for the global economy by 2060 under 2 °C global warming. While OECD countries may benefit, others may suffer GDP losses. In contrast, Mendelsohn, Schlesinger, and Williams [44] predicted cumulative damage of not greater than 0.1 percent of GDP by 2100 at 2.5 °C, with high-latitude countries gaining and low-latitude countries losing. Beyond 2 °C, Mendelsohn, Schlesinger, and Williams [44] suggest that the benefits accruing to high-latitude countries will diminish, while the losses experienced by low-latitude countries will increase. Stern [45] forecasted a modest impact of climate change, around 0.2–2 percent of global GDP by 2100 under 2 °C warming. However, beyond 3 °C, countries will vary significantly in their exposure to climate change risks. These predictions contrast with earlier papers by Fankhauser [41] and Cline [40], which projected a reduction of the world's GDP by 1.5 percent and 1.1 percent, respectively, under temperature increases of 3 °C and 2.5 °C.

Fig. 7 illustrates the global economic loss due to climate change under different damage functions used by Weitzman [51], Nordhaus [29], and Dietz and Stern [28] relative to baseline cases (no climate change scenario) in 2100. The Nordhaus function provides the most optimistic outlook, with economic loss not distinctly different until global warming levels exceed 3 °C, which is similar to Weitzman. The difference widens beyond 4 °C. The Dietz and Stern model indicates significant climate change impacts after

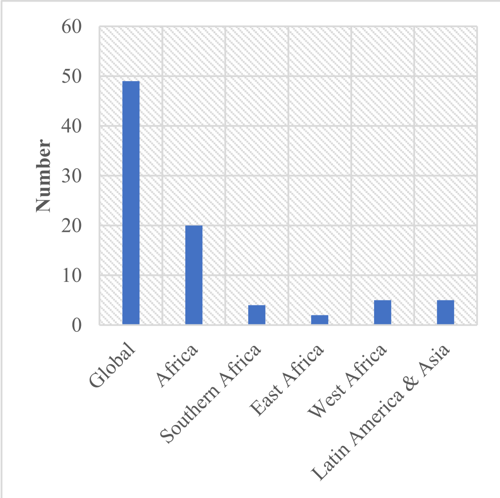

Fig. 4. Distribution of studies by data source.

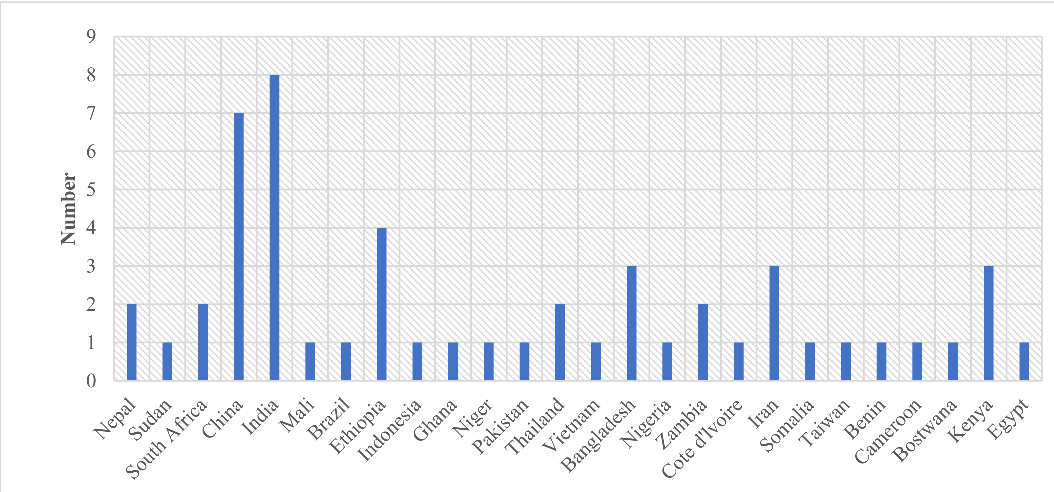

Fig. 5. Distribution of studies by country of focus.
Source: Author's construction.

a temperature increase surpasses 2 °C. All three studies suggest that impacts increase in developing countries but remain small in developed economies. There appears to be a tipping point of 2°C-3°C according to these studies.

Since the publication of these influential studies, other research has examined the future impact of climate change on global, regional, and national economic output. Pretis et al. [53] evaluated the global economic implications of 1.5 °C and 2 °C global warming targets by combining econometric techniques with the Half a degree Additional warming, Prognosis, and Projected Impacts (HAPPI) study. Their findings suggest that the growth effects of climate change are similar at 1.5 °C and 2 °C, but economic growth is more likely to slow at 2 °C. Per capita GDP is projected to decrease by a median of 13 percent under 2 °C and 8 percent under 1.5 °C compared to the base case. The study also indicates that low-income countries will experience greater economic losses than high-income countries across all scenarios.

Burke et al. [32] evaluated the economic damages associated with temperature-increase thresholds of 1.5 °C and 2 °C using global data. To address uncertainty, they employed bootstrapping methods and separate damage functions for each re-sample. Their findings suggest a greater than 75 percent chance that economic damages will be lower if global warming remains below the 1.5 °C threshold compared to reaching 2 °C. Economic output reduction at 2.5°C-3°C warming by 2100 could reach 10 percent by mid-century and between 15 and 25 percent by 2100, rising to over 30 percent at 4 °C warming by 2100. Limiting warming to 1.5 °C could yield accumulated global benefits exceeding US$20 trillion with over a 60 percent chance. At the country level, benefits are unevenly distributed, with tropical and subtropical countries potentially experiencing 10–20 percent higher per capita incomes at 1.5 °C compared to 2 °C. Conversely, some high-latitude countries may see negative growth outcomes under 1.5 °C relative to 2 °C.

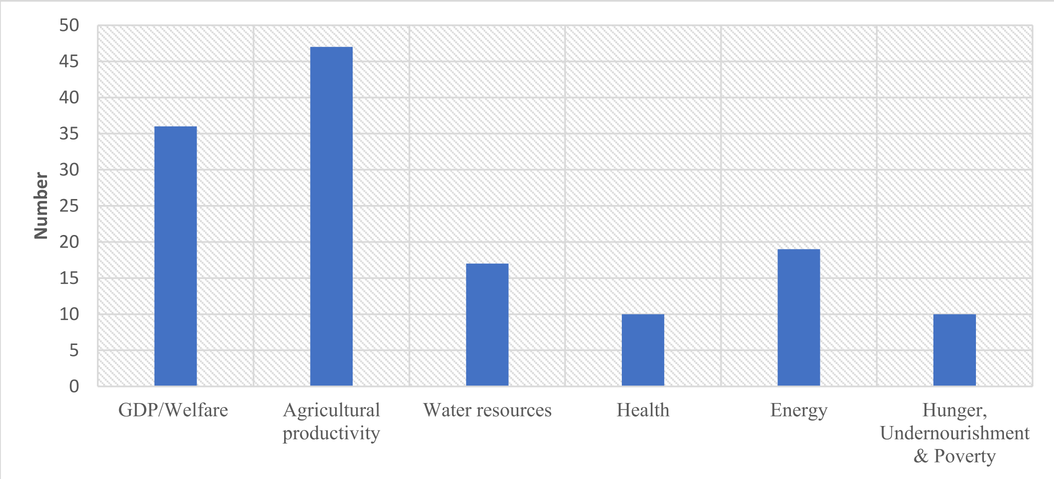

Fig. 6. Distribution of studies by theme.
Source: Author's construction.

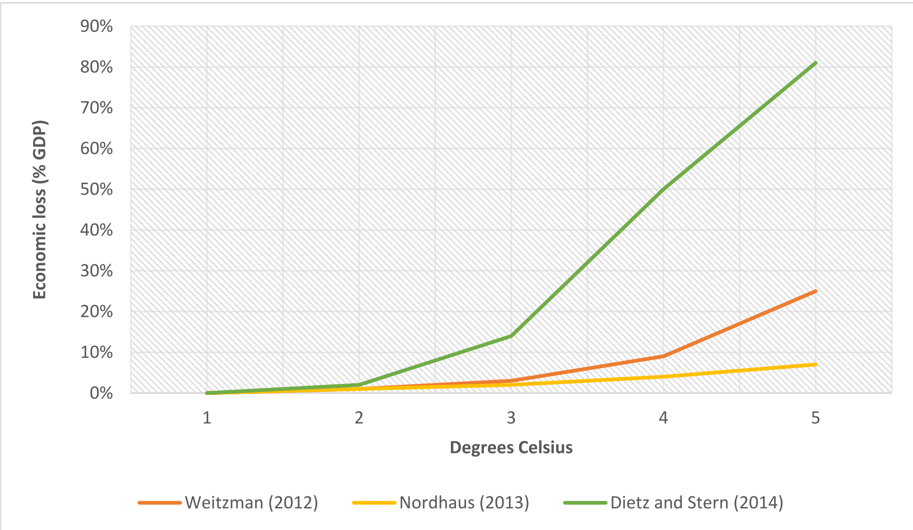

Fig. 7. Economic loss due to climate change under different damage functions.
Source: Covington and Thamotheram [52].

In their global assessment of climate change impact, Kompas et al. [54] support the assertion that beyond 2 °C, the impact of climate change on economic growth would be significantly greater in the long term (by 2100) than in the short and medium term, particularly among developing economies compared to developed economies. Wang et al. [31] conducted a study assessing global, regional, sectoral, and national economic losses from climate change under three scenarios: business as usual, Nationally Determined Contributions (NDC) [i.e., each country or region satisfies their NDC commitments for 2030], and a 2 °C scenario. Using computable general equilibrium modeling–integrated assessment modeling (CGEM-IAM), they projected higher mean temperatures by 2050 under business as usual compared to NDC and the 2 °C scenario. The negative impact on GDP due to climate change is highest under business as usual, followed by NDC and then the 2 °C scenario. By 2030, global economic loss under the business-as-usual scenario is estimated at approximately US$305 billion annually, rising to around US$1.628 trillion by 2050. Economic losses are projected to be approximately 0.25 percent of GDP across sectors in 2030, with agricultural and energy-intensive sectors hardest hit. Developing economies, particularly India and China, will bear the brunt of climate change impacts, accounting for over 40 percent of global GDP losses by 2050. Other developing regions like Southeast Asia, the Middle East, and Africa (excluding South Africa) will also experience significant losses, totaling approximately 85 percent of global GDP loss, while developed economies will account for 15 percent.

Jiang et al. [30] examined the impact of rising temperatures on the economic growth of global economies from 2015 to 2100, focusing on 12 regions including Africa, Latin America, the United States, the European Union, China, India, and the Middle East. Three climate scenarios were used: SSP5-RCP8.5, SSP2-RCP4.5, and SSP1-RCP2.6.[1] Economic losses due to climate change were highest under the SSP5-RCP8.5 scenario. Developing economies were shown to suffer more from climate change across all scenarios compared to developed economies. China, Africa, and the Middle East were particularly hard hit, with China risking 10.7 percent, 4.6 percent, and 3.1 percent of its GDP to climate change under the respective scenarios, while the United States faced lower risks of 3.2 percent, 0.8 percent, and 0.3 percent of output. In Africa, economic losses from climate change are projected to be minimal until 2050, averaging under 2 percent, but could increase significantly beyond this period, ranging from 3 to 10 percent by 2100. Liu and Chen [55] studied the future global socioeconomic risk related to drought, calculated as the product of three determinants: hazard, exposure, and vulnerability. The global population's risk related to drought was projected to be highest in 2046–2065 under scenario SSP3-RCP8.5, with a 63 percent increase in the number of people affected, compared with the base period (i.e., 1986–2005). The highest risk to GDP (4.29×10^{13} purchasing power parity $) was projected in 2046–2065 under scenario SSP1-RCP2.6, with the risk increasing 5.64 times compared to the base period. Regions with high socioeconomic risk are primarily concentrated in East and South Asia, midwestern Europe, the eastern United States, and coastal areas of South America. With climate change, inequality in the future socioeconomic risk of drought among countries is predicted to increase. These findings underscore the heightened socioeconomic risk faced by poor and developing countries due to climate change.

More recent studies by Bilal and Kanzig [4], Waldelich et al. [56], and Kotz et al. [5] predict a much steeper decline in world gross domestic product per capita over the next decades under unfavorable climate scenarios, highlighting similar patterns of regional heterogeneities. Kotz et al. [5] predict that climate change will cause a permanent income reduction of 19 percent within the next 26 years, with a range from 11 to 29 percent. Except for high-latitude regions, all other regions are expected to suffer economic losses due to climate change. Losses will be particularly significant in low latitudes, which currently have low emission and income levels. Waldelich et al. [56] project a 10 percent decline in global GDP under unfavorable climate warming scenarios, with the worst effects in poor, low-latitude countries, experiencing about a 17 percent decline. High-latitude countries are expected to experience reduced impact due to the lower variability in temperature. Economic losses will not be uniformly distributed, as countries in the Global South, such as those in Africa and the Middle East, will suffer more due to their initial temperature levels and greater vulnerability to additional warming. Bilal and Kanzig [4] also predict large macroeconomic effects of climate change, suggesting impacts around six times greater than previously reported by other studies. An increase in temperature by 1 °C is expected to reduce world GDP by 12 percent, equivalent to an economic loss of 31 percent.

Global-level studies highlight key aspects of the economic-climate change relationship. Firstly, there's no consensus on the optimal temperature, with tipping points at either 2 °C or 3 °C; however, impacts are heightened above 2 °C, affecting economies regardless of temperature levels below this. Economies with weak infrastructure, poor technology, and low adaptive capacity will suffer most, suggesting mitigation and adaptation measures will benefit them most. Secondly, the impact of climate change will be greater in the long term than in the short to medium term. The cross-sectional and temporal variations in the impact of climate change indicate a potential risk of widening inequality and reducing growth convergence among countries over time in the future. Diffenbaugh and Burke [46] found that global warming increases economic inequality, widening the gap between top and bottom deciles of global income distribution. Baarsch et al. [34] found climate change might delay income convergence in Africa, projecting slower decline in inequalities in high-warming scenarios, potentially deepening economic inequality within the region.

3.1.2. Asia and Africa case studies

Country-specific and regional studies in developing economies support the aforementioned narratives. In Asia, these studies highlight the negative impact of climate change on economic output. For instance, Cui et al. [57] examined the effects of sea level rise on economic development and regional disparity in China under two scenarios: slow-onset sea level rise (S1) and sudden-onset storm surges (S2). They found greater reductions in GDP under S2 than under S1. Specifically, if sea level rise under S2 features sudden-onset extreme storm surges, coastal regions could experience a GDP loss of up to 11 percent in 2050, compared to 1.97–2.39 percent under S1. Regions like Tianjin, Shanghai, and Jiangsu would suffer the most severe losses, with declines of over 20 percent in their individual GDP by 2050 under S2. Under S1, the most affected areas, such as Guangdong, Jiangsu, and Hainan, would see GDP declines of more than 5 percent.

In Africa, the impact of climate change on economic output follows a similar pattern. Ngepah et al. [58] conducted a study forecasting the impacts of climate change on economic growth in South Africa by 2030 and 2050. They found that compared to 1995–2000 levels, South Africa's economy would lose approximately US$1.8 billion by 2030 under the RCP4.5 scenario and US$2.3 billion under the RCP8.5 scenario. By 2050, these losses would increase to US$1.9 billion and US$2.48 billion, respectively, corresponding to national economic losses of 4.1 percent of GDP under RCP4.5 and 5.08 percent under RCP8.5 in 2030, and 4.11 percent under RCP4.5 and 5.19 percent under RCP8.5 in 2050. This highlights the significant economic costs associated with climate change, even under the best plausible mitigation scenarios.

Baarsch et al. [34] investigated the impact of climate change on incomes in Africa from 2015 to 2050. They analyzed three dimensions of climate risk (exposure, vulnerability, and hazards) using two scenarios (high and low warming). The study projected

[1] These scenario names combine the Shared Socioeconomic Pathways (SSPs) that they are based on with the associated Representative Concentration Pathways (RCPs) for greenhouse gas concentrations in the atmosphere, measured in watts per square meter of radiative forcing.

adverse effects on GDP per capita growth in Africa, with western and eastern Africa expected to be the most affected regions. In these areas, the median estimate of the reduction in per capita GDP for the high-warming scenario compared to the low-warming scenario is over 10 percent by 2050. Conversely, northern and southern Africa are projected to experience a median per capita GDP reduction of less than 10 percent, and Central Africa less than 5 percent in the high-warming scenario. Overall, the study indicated that the macroeconomic risk of climate change is twice as high in the high-warming scenario compared to the low-warming scenario across all regions by 2050.

Kompas et al. [54] discovered that the impact of climate change on economic growth in Africa varies across subregions, degrees of warming, and time spans. They identified western and eastern Africa as the regions most vulnerable to climate change. The negative impact was observed across all scenarios but intensified notably beyond the 2 °C warming threshold. Fig. 8 illustrates the projected mean and median climate change impact on GDP at 3 °C global warming for different periods in Africa. The graph indicates that until 2050, the expected economic loss as a percentage of GDP due to climate change in Africa is minimal. Therefore, over the next three decades, African economies might not experience significant damage from climate change. However, beyond 2050, the loss in economic output due to climate change is anticipated to be substantial. By 2100, the percentage change in per capita GDP compared to a no-warming scenario could reach as high as −7.5 percent. Dinar et al. [59] projected a continent-wide reduction in GDP ranging from 6 to 100 percent by 2100 in Africa, based on various climate models, compared to a scenario with no warming. This reduction was exempted for two or three countries where climate change might bring positive benefits. The broad range in potential impact scales is attributed to the diversity of temperature predictions generated by different climate models. For instance, pessimistic scenarios, like those from the University of Illinois Urbana-Champaign, forecast substantial warming near the equator but moderate warming near the poles. In contrast, optimistic models such as Pollard and Thompson's Global ENvironment and Ecological Simulation of Interactive Systems (GENESIS) predict a modest temperature increase near the equator but a more significant rise in temperature in temperate and polar zones.

From an African perspective, there's a consensus that climate change could impede economic growth in the region, potentially exacerbating poverty levels compared to a scenario without warming. Table 2 summarizes various studies on climate change's impact on economic output in Africa, comparing them to preindustrial average temperatures. The studies assume different degrees of warming: Tol [48] assumes 1 °C, Baarsch et al. [34] 8.5 °C, Kompas et al. [54] 1°C-4°C, and others 2.5 °C. On average, these studies project economic losses of 7.12 percent, with a median of 4.82 percent and a standard deviation of 5.86 percent, indicating significant heterogeneity in estimated impacts. Even within the same global warming scenario of 2.5 °C, projected economic output losses vary widely, from 0.5 percent to 14.6 percent. Overall, there's no discernible tipping point in the economic effects of global warming for Africa; any increase from current levels is predicted to reduce output.

Within Africa, the impact of climate change varies across regions and even within subregions. Fig. 9 illustrates the estimated mean and median impact of climate change on GDP per capita by subregion in Africa under a 3 °C global warming scenario. The severity of the impact differs across regions, with Western and Eastern Africa experiencing the most significant effects but at different times. While Western Africa is likely to face severe reductions in GDP per capita in the next two decades, the impact in Eastern Africa is expected to be more pronounced after four decades.

Even within subregions, there is heterogeneity in the impact. Fig. 10 shows the climate impact on output for various African countries assuming 3 °C warming. For example, in western Africa, Togo, Ghana, Burkina Faso, Nigeria, and Côte d'Ivoire are projected to be the hardest hit countries by 2100, while in eastern Africa, Malawi, Mauritius, Kenya, and Mozambique are expected to be most

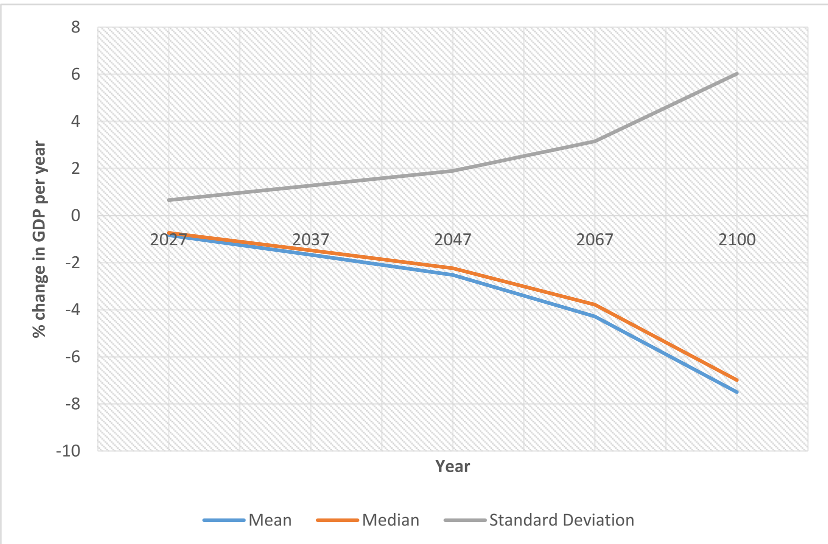

Fig. 8. Projected impact of climate change on GDP over time at 3 °C for Africa.
Source: Author's construction using data and original projections from Kompas et al. [54].

Table 2
Impact of climate change on economic output in Africa.

Study author	Year of publication	Degree of warming	Percentage change in GDP	Forecast year
Tol	[43]	2.5 °C	−8.7	2100
Nordhaus and Yang	[60]	2.5 °C	−2.1	2100
Plambeck and Hope	[61]	2.5 °C	−8.6	2200
Mendelsohn, Morrison et al.	[27]	2.5 °C	−3.6	2100
Mendelsohn, Schlesinger, and Williams	[44]	2.5 °C	−0.5	2100
Nordhaus and Boyer	[62]	2.5 °C	−3.9	2100
Tol	[48]	1.0 °C	−4.1	2050
Hope	[63]	2.5 °C	−2.6	2100
Baarsch et al.	[34]	2.6 °C–8.5 °C	−4.0 to −8.0	2050
Kompas et al.	[54]	1.0 °C	−2.2	2100
Kompas et al.	[54]	2.0 °C	−4.9	2100
Kompas et al.	[54]	3.0 °C	−8.1	2100
Kompas et al.	[54]	4.0 °C	−11.8	2100

Source: Author's compilation from the literature.

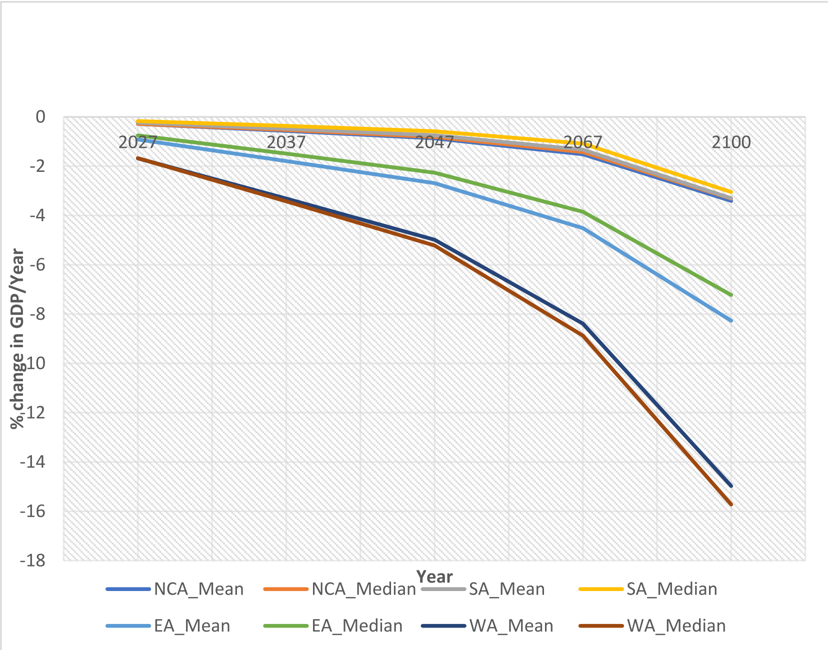

Fig. 9. Regional heterogeneity in climate change impact at 3 °C over time.
Note: EA = eastern Africa; NCA = northern and central Africa; SA = southern Africa; WA = western Africa.
Source: Authors' construction using data from Kompas et al. [54].

affected in the long term. Fig. 11 further highlights the variation in African countries' exposure to different levels of global warming.

The impact of climate change on Africa's economic growth is highly variable, with significant differences observed across regions and even within subregions. These variations highlight the necessity for region-specific and country-specific climate policies that address the unique challenges and resilience capacities of each area. However, the current scientific understanding of the sources of these heterogeneities remains limited, especially for high-risk countries in Africa. To design effective climate policies and adaptation strategies, it is crucial to enhance research efforts to better understand the diverse impacts of climate change across different regions and subregions.

3.2. Impact of climate change on agricultural productivity

The primary sector, critical for most developing economies, is highly susceptible to climate change due to its reliance on temperature and precipitation. Climate change is expected to affect agricultural activities by impacting farmland and labor productivity, as well as food security, over several decades, despite mitigation efforts [1]. Factors contributing to reduced food production include direct alterations to agroecological conditions, indirect effects on demand, income distribution, and economic growth, and a decrease in suitable agricultural land availability [64]. Some argue that climate change's impact on farming in developing countries might lead

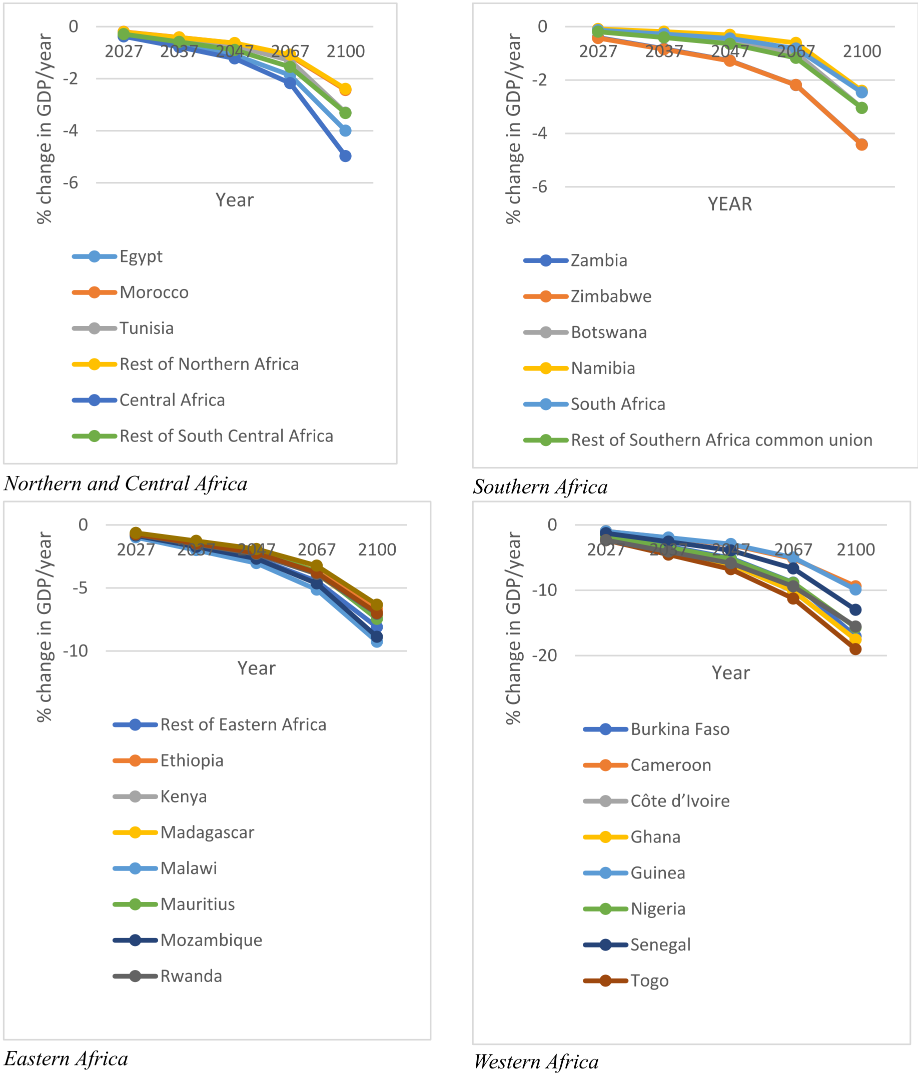

Fig. 10. Country-level heterogeneity in climate change impact at 3 °C over time.
Source: Author's construction using data from Kompas et al. [54].

to gains for farming households due to increased food prices resulting from decreased agricultural output [1]. This section reviews studies on the projected future impact of climate change on food security and land use to identify emerging trends and patterns.

3.2.1. Food security

3.2.1.1. Global level studies. UN Sustainable Development Goal (SDG) targets 2.1 and 2.2 aim to end hunger, ensure access to safe, nutritious, and sufficient food year-round, and eradicate malnutrition. Pre-COVID-19, food security indexes remained relatively stable since 2015. However, the pandemic led to a significant increase in food insecurity globally, with approximately 2.3 billion people facing moderate or severe food insecurity [65]. The prevalence of undernourishment rose from 8 % in 2019 to 9.8 % in 2021, with Asia, Africa, Latin America, and the Caribbean being the most affected regions [65]. In 2021, 425 million, 278 million, and 56.5 million people were undernourished in Asia, Africa, and Latin America/Caribbean, respectively [65]. Climate change's impact on the global food supply chain raises concerns about future extreme food insecurity. This section explores literature on developing economies, particularly Africa, to assess potential future food security issues due to climate change.

At a global level, studies indicate that climate change's impact on agricultural output is expected to be relatively small, but significant variations exist across different regions (see Fig. 12). Fischer et al. [66] evaluated the effect of climate change on agricultural GDP to be moderate on a global scale, ranging from −1.5 percent to +2.6 percent compared to baseline projections. This translates to a monetary loss of US$2.9 trillion to US$3.6 trillion (1990 US dollars). Developing countries are projected to experience the most pronounced negative impact, with North America and the former Soviet Union expected to see agricultural GDP gains of 3.13 percent

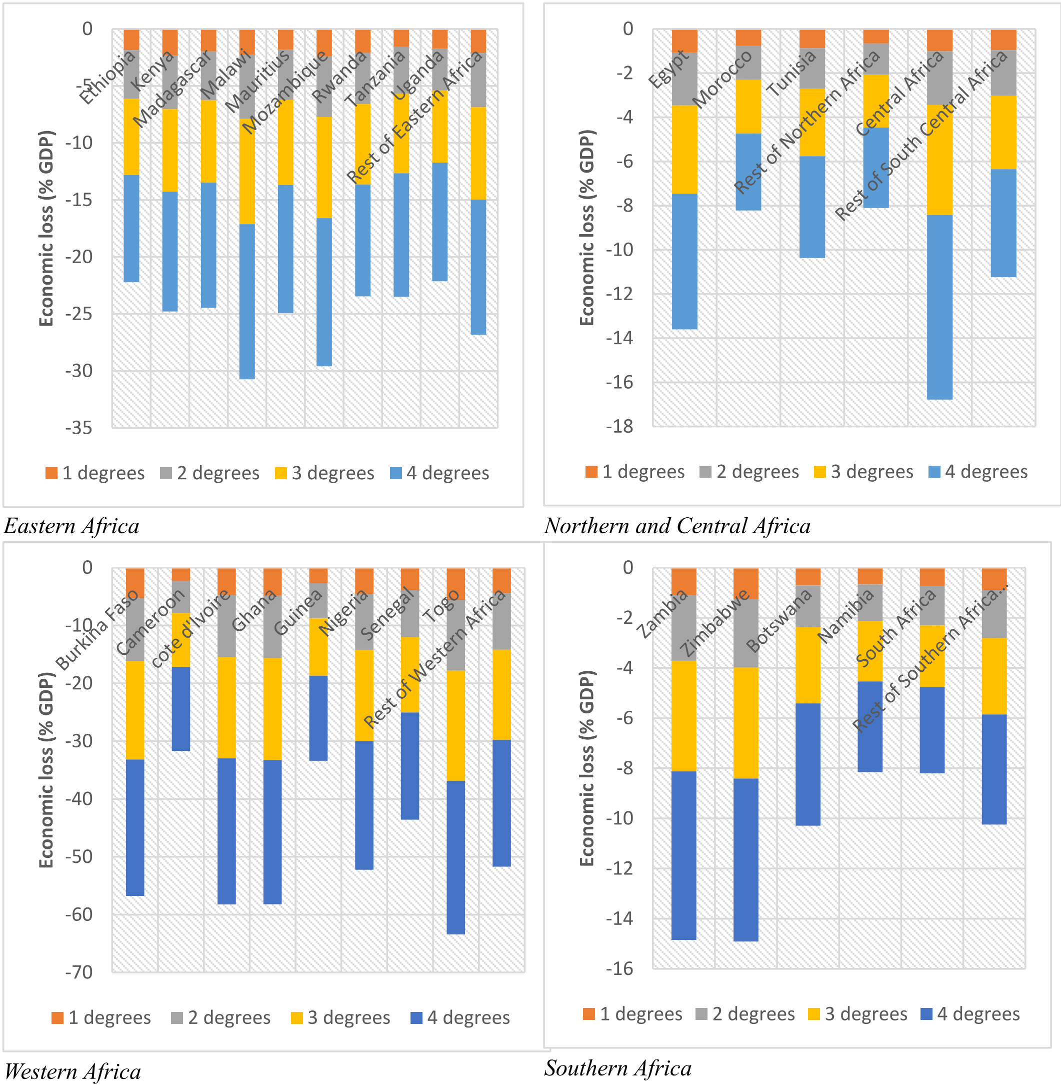

Fig. 11. Subregional climate change impact on GDP in Africa by varying temperatures.
Source: Author's construction using data from Kompas et al. [54].

and 23 percent, respectively. Conversely, Western Europe may witness a decline in agricultural GDP by 6–18 percent. In developing nations, agricultural GDP is anticipated to decrease, with Asia and Africa facing potential declines of 4 percent and 2–9 percent, respectively, by 2080 compared to baseline levels.

Valenzuela and Anderson [1] conducted a simulation study using global data, revealing that the response of yield to climate change shocks is expected to be negative in developing countries but positive in high-income countries. They anticipate a reduction in agricultural output in developing countries by 1.9 percent by 2030 and 4.3 percent by 2050 compared to a no-warming scenario. Particularly in Africa, the decline is projected to be steep, with sub-Saharan Africa excluding South Africa expected to experience a 2.9 percent decrease in agricultural output by 2030 and 6.8 percent by 2050. Conversely, Latin America may see decreases of 1 percent and 4.9 percent in agricultural output by 2030 and 2050, respectively. The impact of climate change on agricultural output is forecasted to be moderate in the next decade but significant thereafter. As agricultural output decreases, agricultural prices are expected to change in the opposite direction, potentially leading to a rise in agricultural value added for some developing countries.

Studies by Calzadilla et al. [67], Gurgel et al. [68], Molotoks et al. [69], Wiebe et al. [70], Li et al. [71], and Schmidhuber and Tubiello [64] corroborate the adverse impact of climate change on global agricultural production, with regional variations. Calzadilla et al. [67] project a global decline in agricultural production by 0.5 percent in the medium term and 2.5 percent in the long term compared to a no-climate-change scenario, with the Middle East, South Asia, and Africa anticipated to be most affected. Their study reveals that, in Africa, total crop production decreases in both pessimistic and optimistic scenarios when considering precipitation alone, precipitation plus carbon dioxide fertilization, water alone, and water plus land factors. Rainfed crop production is expected to suffer more than irrigated crop production, with rainfed crop production declining due to heat stress by 2050 despite moderate

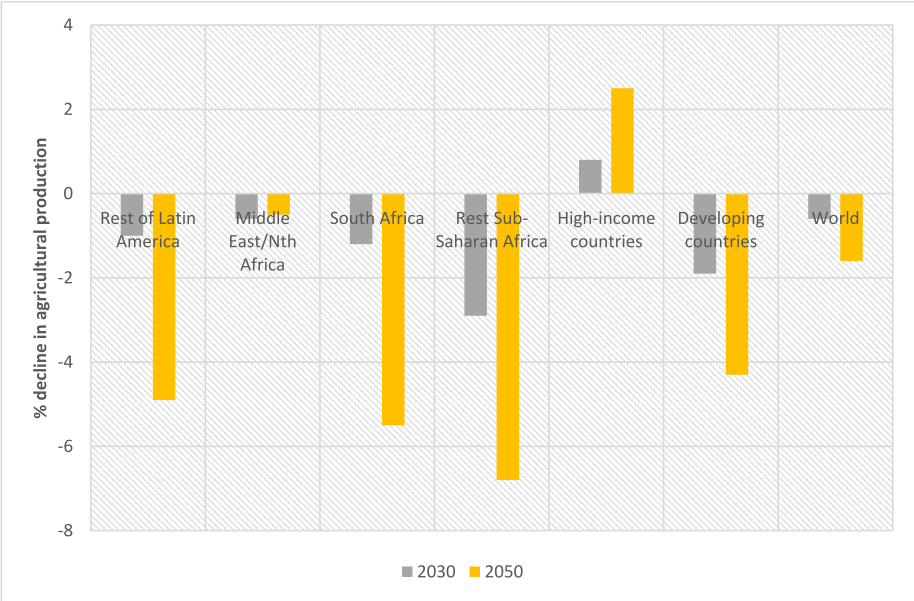

Fig. 12. Climate change impact on agricultural output.
Source: Author's construction.

precipitation potentially reducing the yield gap between rainfed and irrigated crop production in the 2020s.

The anticipated decline in agricultural production is expected to lead to a global increase in agricultural prices. Projections suggest that this increase in world food prices will be significantly greater in 2050 compared to 2020 under both pessimistic and optimistic scenarios. Specifically, for cereal grains, sugarcane, sugar beet, and wheat, world food prices are forecasted to rise between 39 and 43 percent by 2050, depending on the emissions scenario considered.

Wiebe et al. [70] combined socioeconomic models with climate change models and developed three case scenarios: an optimistic scenario (SSP1-RCP4.5), with slow growth in population, fast growth in income, and slow growth in greenhouse gas emissions; a pessimistic scenario (SPP3-RCP8.5), with fast population growth, slow growth in income, and fast growth in greenhouse gas emissions; and an intermediate case (SSP2-RCP6). Their study also projects that at the global scale, yields of major crops will decline by 5–7 percent relative to levels in 2050 in the absence of climate change under the SSP1-RCP4.5 and SSP3-RCP8.5 scenarios. In absolute terms, this represents a loss of about a tenth of the projected growth due to improved management practices and technology. The total global production and consumption of five food crops is projected to decline by 1 percent in 2050 relative to the levels expected in the absence of climate change. Higher-latitude areas are likely to experience less impact than lower-latitude areas. Due to the decline in output, prices are expected to increase by 10–15 percent, doubling the increases projected in the absence of climate change. The decline in agricultural yield projected by Wiebe et al. [70] is smaller than that projected by Nelson et al. [72], who predicted an 11 percent decline in yield and a 20 percent rise in prices for the SSP2-RCP8.5 case. The observed differences could be due to variations in the models. For example, Wiebe et al. attempted to introduce greater flexibility into the model in response to different climate change situations, such as less-extreme pathways, updates in the definition of the drivers of SSPs, and the inclusion of sugar as a crop. However, Wiebe et al. did not account for carbon dioxide fertilization and excluded other important climate change effects such as extreme temperature and precipitation, melting of glaciers, and rising sea levels.

Hertel et al. [21] estimated a wide range of potential food price changes by 2030. In the low-productivity scenario, prices for major staples could rise by 10–60 percent, while in the medium-to high-productivity scenario, prices might decline, especially in the high-productivity scenario, where they could decrease by 5–20 percent. Nelson et al. [35] found that, in the optimistic (high income growth and low population growth) and pessimistic (low income growth and high population growth) cases, climate change would reduce daily caloric availability in developing and low-income countries, with larger declines expected in low-income countries both in 2010 and 2050. While yield growth might be higher for some crops in low-income countries compared to middle-income countries, this doesn't apply to important irrigated crops.

Table 3 provides a summary of the predicted yield changes between 2010 and 2050 due to climate change for various crops across different geographical locations. The values represent averages for scenarios with temperature increases of 1.4 °C and 2.8 °C. In developed economies, maize, rice, and wheat yields are predicted to decline more for rainfed crops than for irrigated ones. Conversely, in developing economies and middle-income developing countries, the reverse is true. The situation is mixed for low-income countries; while for some crops like maize and rice, irrigated crops will be more affected by climate change, for wheat crops, rainfed yields will suffer more than irrigated ones. This suggests that the impact of climate change on rainfed versus irrigated crops might vary depending on the geographical context.

In a scenario without climate change mitigation, individual crop prices are projected to increase significantly between 2010 and

Table 3
Predicted yield change (%) between 2010 and 2050 due to climate change.

Region	Maize		Rice		Wheat	
	Irrigated	Rainfed	Irrigated	Rainfed	Irrigated	Rainfed
Developed	−9.01	−17.14	−9.30	−12.96	−8.52	−6.47
Developing	−4.56	−2.16	−10.84	−0.47	−11.78	−7.27
Low-income	−3.20	−1.82	−9.42	+0.51	−11.33	−14.90
Middle-income developing	−4.62	+2.21	−11.14	−9.85	−11.81	−6.86
World	−5.74	−7.00	−10.80	−0.98	−11.57	−6.97

Source: Author's computation using the original figures presented by Nelson et al. [35]. These figures represent the average predicted effect for the two global warming scenarios (1.4 °C and 2.8 °C) for 2050.

2050. For rice, the price rise ranges from 31.2 percent in the optimistic case to 78 percent in the pessimistic case, compared to the baseline of 58 percent. For maize, the price change varies from 87.3 percent in the optimistic scenario to 106.3 percent in the pessimistic scenario, relative to the baseline of 100.7 percent. However, with climate change mitigation measures in place, the price increases are expected to be lower than in the absence of mitigation.

Berhane [73] highlighted significant yield decreases in low-latitude areas due to climate change. Li et al. [71] simulated the impact of global warming on maize production, showing that yield changes depend on the warming level, time, and location. At 2 °C warming, maize yields are projected to decrease by 10.8 percent, whereas at 1.5 °C warming, yields might slightly increase by 0.18 percent. The most substantial losses are expected in the middle- and lower-latitude areas of South America, Asia, and the middle latitudes of Africa and North America.

The comprehensive body of research on the impact of climate change on global agricultural production paints a concerning picture of the future of food security and economic stability. Across different regions and scenarios, the consensus is clear: climate change poses a significant threat to agricultural yields, with developing countries projected to bear the brunt of the negative consequences. These studies indicate that the anticipated decline in agricultural production, coupled with an increase in world food prices, could exacerbate food insecurity and economic disparities, particularly in regions highly dependent on agriculture for livelihoods and sustenance. Moreover, the expected impacts extend beyond crop yields, with implications for agricultural GDP, market dynamics, and overall economic stability. While some regions and scenarios may fare better than others, the overarching trend points towards a challenging future for global food systems.

3.2.1.2. Region/country specific case studies

3.2.1.2.1. Asia case studies. Specific region and country case studies also indicate significant negative impacts of climate change on crop yields, often showing larger reductions than global-level studies. Khan et al. [74] examined the economic effects of climate change on agriculture in Pakistan and projected that by 2050, climate change–induced losses in wheat and rice production will reduce Pakistan's real GDP by US$19.5 billion. This corresponds to a 14.7 percent reduction in wheat yield and a 20.5 percent reduction in rice yield compared to a no-climate-change scenario.

Chalise et al. [75] examined the economic impact of climate change–induced loss of agricultural productivity in Nepal, revealing significant negative effects on the economy, particularly for rural households reliant on subsistence farming. The study's simulations indicated a real GDP decrease of 10.03 percent in the highest-impact scenario, 6.56 percent in the medium-impact scenario, and 2.49 percent in the lowest-impact scenario by 2050. Climate change is expected to reduce agricultural output by 6.7–7.6 percent from baseline levels. Specific crop yields are also projected to decline, with rice yields falling by 0.8–7.22 percent, wheat by 1.28–5.45 percent, and cereal grains by 2.43–8.43 percent across various scenarios.

Do Prado Tanure et al. [76] studied the impact of climate change on the Legal Amazon region's agriculture and economy between 2030 and 2049. They found that a climate-driven drop in economic indicators will lead to a 1.18 percent loss in real GDP by 2049 due to decreased agricultural production and employment. Crop yields are projected to decline: rice by 7.55 percent, corn by 7.9 percent, soybeans by 7.87 percent, and sugarcane by 11.34 percent.

Srivastava et al. [77] examined climate change's impact on maize yield in eastern India. For irrigated areas, maize yield is projected to decrease by 10.58–23.39 percent from 2021 to 2050 and by 15.20–26.83 percent from 2051 to 2080. For rainfed maize, yield changes are less significant, ranging from −10.55 percent to +9.20 percent (2021–2050) and +4.31 percent to +10.63 percent (2051–2080). Thus, irrigated maize faces greater losses than rainfed maize, as future higher rainfall could make irrigation less effective.

Jiang et al. [78] studied climate change impacts on rice yields in Vietnam's Mekong River Delta. They found that rainfed rice yields are projected to decline by 35 percent in 2020–2029, 16 percent in 2030–2039, and 21 percent in 2040–2050 due to decreased rainfall during winter. Conversely, irrigated rice yields are expected to rise by 11 percent in the 2020s but decrease by 0.5 percent in the 2030s and 23 percent in the 2040s. During summer, rainfed rice yields are predicted to fall by 49 percent in the 2020s, 56 percent in the 2030s, and 40 percent in the 2040s. However, irrigated rice yields may decrease by 5 percent in the 2020s but increase by 2 percent in the 2030s and 5 percent in the 2040s due to higher predicted rainfall.

Sinnarong et al. [79] and Ansari et al. [80] found that climate change negatively affects rice production. Sinnarong et al. [79] projected a mean rice production decrease in Thailand by 9.37 percent in 2030 and 33.77 percent in 2090, with the greatest impact in the north (2.01 percent in 2030 to 11.61 percent in 2090). Ansari et al. [80] predicted that changing rainfall, rising temperatures, and increased solar radiation could reduce rice yields in Indonesia across all growing seasons, with the second dry season experiencing up to a 12 percent decline by the 2050s under the RCP8.5 scenario. These results underscore the importance of spatial and temporal variations in the impact of climate change on crop yields.

Climate change is expected to negatively affect various crops, including wheat, potato, and sugarcane. Kumar et al. [81] projected a reduction in wheat yield in India by 6–23 percent by 2050 and by 15–25 percent by 2080 compared to a no-climate-change scenario. The severity of these impacts varies with emission levels, sowing times, and spatial location, with late-sown and warmer central and south-central regions being more affected. While carbon dioxide fertilization might offer some benefits, regions with high seasonal temperatures will still see reduced yields. Adaptation measures (i.e., use of efficient inputs and changes in sowing times) could mitigate yield reductions to 9 percent in 2050 and 13 percent in 2080.

Scott et al. [82] examined future potato production scenarios in India using various economic, crop, climate, and water models. They assessed three scenarios: optimistic (SSP1-RCP4.5: high economic growth, low population growth, favorable climate), middle-of-the-road (SSP2-RCP6: moderate economic and population growth, challenging climate), and pessimistic (SSP3-RCP8.5: slow economic growth, high population growth, adverse climate). Predictions showed potato production in India increasing from 2010 to 2030, ranging from 37.6 million metric tons in the optimistic scenario to 23.9 million metric tons in the pessimistic scenario. Yield increases varied from 19.9 to 27.1 metric tons per hectare under different assumptions, with annual compound growth rates ranging from 1.48 percent to 0.8 percent.

Pipitpukdee et al. [83] investigated the impact of climate change on sugarcane production in Thailand under RCP4.5 and RCP8.5 scenarios. They found that climate variables and increased population density influenced sugarcane yield and harvested area. The study projected a decrease in sugarcane yield, harvested area, and production by 23.95–33.26 percent, 1.29–2.49 percent, and 24.94–34.93 percent, respectively, during 2046–2055 compared to the baseline period of 1992–2016. The reduction in production was more severe under adverse climatic conditions (RCP8.5) than under mild conditions (RCP4.5), particularly in the eastern and lower sections of Thailand's central regions. This decline could negatively impact the livelihoods of one million sugarcane growers and destabilize sugar prices in the global market.

The studies on Asia underscore the adverse effects of climate change on crop yields, influenced by factors such as agroecological conditions, crop type, and available adaptation measures. While some crops exhibit greater resilience to climate change impacts even under severe scenarios, there's a notable lack of research focusing on understanding the dynamics of crop resilience to climate change. Understanding these dynamics is crucial for devising effective adaptation strategies aimed at supporting vulnerable groups and addressing food insecurity. Therefore, further research into crop resilience dynamics to climate change is essential for informing robust adaptation policies and interventions in the agricultural sector.

3.2.1.2.2. Africa case studies. Schlenker and Lobell [84] examined the effects of climate change on agricultural crops in Africa, finding median production decreases of 22 percent for maize, 17 percent for sorghum, and 17 percent for millet by mid-century compared to a no-climate-change scenario. In a more recent study, Emediegwu et al. [85] projected a larger decline in millet yield under the RCP8.5 scenario for the period 2040–2069, with a projected reduction of 48–55 percent compared to a no-climate-change scenario.

Thornton et al. [86] investigated the repercussions of climate change on agricultural systems and households in East Africa, estimating an average production loss of 8 percent by 2050 compared to a no-climate-change scenario. However, impacts varied by country and agroecological zone. While Burundi (9.1 percent), Kenya (15.8 and 17.8 percent), and Rwanda (10.8 percent and 14.9 percent) are projected to experience increases in maize production by 2030 and 2050, Tanzania and Uganda may face decreases of 3.1 percent and 8.1 percent and 2.2 percent and 8.6 percent, respectively. Bean production changes similarly vary across countries, with positive effects in most nations in 2030 but turning negative by 2050. Agroecological zones also influence outcomes, with temperate regions generally experiencing more positive effects on maize and bean production than humid zones. These findings underscore the nuanced temporal and spatial dynamics of climate change impacts on agricultural production in Africa, which requires further research.

Roudier et al. [39] analyzed the future climate change impacts on crop yields in West Africa, observing a larger impact in northern West Africa[2] (−18 percent median response) compared to southern West Africa[3] (−13 percent median response), attributed to drier and warmer conditions projected for the north. Additionally, they found that as warming intensifies, the negative impacts on crop productivity become more severe.

Ben Mohamed et al. [87] evaluated the influence of current climate variability and future climate change on millet production in Niger. They projected that by 2025, the average millet yield will decrease by 13 percent due to climate change.

Adejuwon [88] investigated the impact of climate change on food crops in Nigeria across different periods (2010–2039, 2040–2069, and 2070–2099) and locations (low- and high-latitude areas). With a 4 °C global warming scenario, maize and rice yields are projected to decline by 11 percent and 22 percent, respectively, compared to the baseline. Paeth et al. [89] assessed climate change effects on crops in Benin by 2025, finding reduced yields for maize, rice, and sorghum by 4 percent, 3.5 percent, and 2.5 percent, respectively, while cotton, yam, and manioc showed some resilience. Tingem et al. [90] studied Cameroon's crop response to climate change under A2 (pessimistic, high) and B2 scenarios (optimistic, medium-low). Maize and sorghum yields may decrease by 14.6 percent and 33.9 percent by 2080 under the A2 scenario, while soybean yields could increase by 12.9 percent, with adaptation strategies potentially offsetting some of these impacts.

[2] The Sudano-Sahelian countries of Niger, Mali, Burkina Faso, Senegal, and the Gambia.

[3] The Guinean countries of Benin, Togo, Nigeria, Ghana, Liberia, Sierra Leone, Cameroon, Guinea, Guinea Bissau, and Côte d'Ivoire.

In addition, Siddig et al. [91] explored climate change's effects on agriculture in Sudan, considering impact pathways beyond mean rainfall and temperature alterations. By 2050, under drier conditions, rainfed maize yield could decrease by 59.5 percent, while millet might see a 13.9 percent increase, sorghum a 14.3 percent decrease, and sesame a 24.5 percent decrease compared to scenarios without climate change.

Butt et al. [92] examined the economic and food security implications of climate change in Mali. They projected crop yield changes ranging from a decrease of 17 percent to an increase of 6 percent at the national level by 2030 compared to a baseline scenario. Forage yields were expected to decline by 5–36 percent, and livestock weights would decrease by 14–16 percent. Economic losses due to these declines were estimated between US$70 and US$142 million, with producers gaining while consumers losing. However, adaptation interventions could mitigate these impacts, reducing yield decreases for maize, sorghum, and millet to 8.6–10.3 percent, 4.3–7.7 percent, and 0.7–8.3 percent, respectively.

Fosu-Mensah et al. [93] investigated the effects of climate change and variability on maize yield in the subhumid zone of Ghana under rainfed conditions. They projected a potential shift in planting dates of the rainy season by six weeks from the third week of March to the second week of May. Climate change was associated with an estimated average yield reduction of 19 percent and 14 percent for the Obatanpa maize variety under the A1B (high economic and population growth; 1.6 °C warming) and B1 (convergent economic growth with stable population growth; 1.3 °C warming) scenarios, respectively, with similar reductions of 20 percent and 18 percent for the Dorke maize variety. Increased yield variability was also anticipated under both scenarios.

Solomon et al. [94] examined climate change's impact on agricultural production in Ethiopia, projecting significant declines over the next four decades, with severity worsening over time. They anticipate teff, maize, and sorghum production to decrease by 25.4 percent, 21.8 percent, and 25.2 percent, respectively, by 2050 compared to the base period, leading to a 31.1 percent loss in agricultural GDP. These estimates assume no adaptation occurs within the forecast period. While Ethiopia's agriculture heavily relies on weather, adaptation measures gradually integrated over time may mitigate the predicted impacts, potentially reducing the severity.

The studies focusing on Africa are sparse but collectively demonstrate the diverse and intricate impacts of climate change on agricultural production in Africa. They underscore the negative repercussions on staple crops and the broader economic and food security implications for communities dependent on agriculture. However, amidst these challenges, the research highlights the potential for adaptation measures to alleviate some of these effects, offering pathways to protect agricultural livelihoods and ensure food security. Ultimately, the findings emphasize the importance of coordinated efforts at various levels to address climate change and support vulnerable populations in adapting to its consequences.

Table 4 provides a summary of the predicted impact of climate change on major crop yields, with some bias toward Africa. The following can be deduced from the table. First, the scope of studies on the impact of climate change on agriculture is quite diverse, making cross-country and cross-regional comparisons challenging. This diversity highlights a significant gap in the global evidence base regarding the impact of climate change on specific crops. Consequently, this gap poses a policy challenge at both global and regional levels, underscoring the need for further research to inform effective policy development.

Second, most studies focus on maize, sorghum, rice, and millet, with fewer studies on other crops. Generally, studies from Asia and Africa report negative impacts of climate change on rice yield, particularly severe in Pakistan, Thailand, India, and Nigeria. The evidence for sorghum, maize, and millet is mixed. Climate change's impact on maize yield appears to be moderately negative in Asia compared to a more pronounced impact in Africa.

Third, different crops exhibit varying degrees of resilience to climate change depending on geography. For instance, maize shows resilience in Rwanda, Kenya, and Burundi, but is less resilient in Sudan, Ghana, Nigeria, Mali, Cameroon, Botswana, and Benin. Similarly, sorghum is resilient in Nigeria but vulnerable in Sudan, Ethiopia, Mali, Cameroon, and Botswana. These variations suggest that some crops may perform well even under unfavorable climate conditions in specific regions. Understanding these spatial dynamics and agroecological differences is crucial for predicting climate change impacts and implementing effective adaptation strategies.

The impact of climate change varies temporally and spatially, indicating heterogeneous risks across time, crops, irrigation statuses, and geography. High-risk areas should be prioritized, with evidence suggesting that in Africa, the highest-risk regions are in the west and east.

Many studies discussed assume no adaptation, leading to upward-biased estimates of climate change impacts on crop yields. This assumption is unrealistic, as adverse effects will likely induce behavioral changes. When adaptation mechanisms are included in models, the negative impact on crop yields is reduced. However, even with adaptation, negative yield impacts persist, indicating that adaptation alone may not fully mitigate the adverse effects of climate change.

3.2.2. Farmland

The threat of climate change to agriculture is evident through its impact on land use and value. Population growth and climate change are reducing the availability of useable agricultural land, which may severely constrain future food production and consumption. Pastor et al. [98] highlighted that an additional 100 million hectares of land would be needed to double food production by 2050 to meet projected food demand. This underscores the importance of understanding the nexus between climate change and land use and value within the agricultural value chain and the global food system. However, research in this area has predominantly focused on developed economies (see [99–105]), where reliable data is more accessible. Studies from developing economies remain limited, although there is a general consensus on the negative impact of climate change on farmland value, with significant temporal and spatial variations.

Seo and Mendelsohn [100] investigated the impact of climate change on farmland value in Latin America by analyzing data from over 2500 farmers across seven countries. The study found that summer warming negatively affects farmland values for both small and large farms, with a 1 °C increase leading to an average decrease of US$175 per hectare. Small farms are more vulnerable to temperature

Table 4
Summary of studies on the impact of climate change on crop yield with reference to a No-climate-change scenario.

Study author	Country/region	Crop (% change in yield)							Year	Degree of warming (°C)
		Millet	Wheat	Rice	Sorghum	Corn/maize	Soybean	Sugarcane		
Khan et al. [74]	Pakistan		−14.70	−20.50					2050	3.30
Sinnarong et al. [79]	Thailand			−9.37 to −33.77					2030 to 2090	3.50 to 12.55
Chalise et al. [75]	Nepal		−1.28 to −5.45	−0.80 to −7.22		−2.43 to −8.43			2030 to 2050	1.60 to 2.90
do Prado Tannure et al. [76]	Legal Amazon			−7.55		−7.90	−7.87	−11.34	2049	1.40
Pipitpukdee et al. [83]	India							−23.95 to −33.26	2046 to 2050	4.50 to 8.50
Jiang et al. [78]	Mekong River Delta			−35.00					2050	1.00
Siddiq et al. [91]	Sudan				−14.30	−59.50			2050	3.64
Thornton et al. [86]	Tanzania					−3.10 to −8.10			2030 to 2050	
	Uganda					−2.20 to −8.60			2030 to 2050	
	Rwanda					+10.80 to +14.90			2030 to 2050	
	Kenya					+15.00 to +17.80			2030 to 2050	
	Burundi					+9.10			2030 to 2050	
Fosu-Mensah et al. [93]	Ghana					−14.19			2050	
Solomon et al. [94]	Ethiopia				−25.20	−21.80			2050	
Adejumo [88]	Nigeria	+4.10		−22.00	+2.90	−11.00			2035 to 2085	2.00 to 4.00
Ben Mohammed et al. [87]	Niger	−13.00							2025	
Butt et al. [92]	Mali	−6.30 to −11.50			−11.50 to −17.10	−11.20 to −13.50			2030	
Chipanshi et al. [95]	Botswana				+10.00 to +31.00	+10.00 to +36.00				
Tiet al. [96]	Cameroon				−33.90 to −39.90	−8.20 to −14.60	+54.60 to +64.40		2080	2.50 to 3.50
Jones and Thornton [97]	West Africa					−10.00			2055	
Paeth et al. [89]	Benin			−2.50	−3.50	−4.00			2020 to2025	
Schlenker and Lobell [84]	Sub-Saharan Africa	−17.00			−17.00	−22.00			2046 to 2065	
Emediegwu et al. [85]	Africa	+48.00 to +55.00							2040 to 2069	

Source: Author's own compilation using data from the literature.

increases, experiencing a drop of US$111 per hectare compared to US$78 per hectare for large farms. Conversely, summer rains can boost farmland values, especially benefiting smallholders. Projections under a severe Canadian climate Centre scenario predict farmland value declines of 20 percent by 2060 and 53 percent by 2100. Smallholder farmers might see their land value decrease by 36–61 percent by 2100, highlighting the disproportionate impact on poorer farmers and the need for interventions to mitigate these effects.

Hossain et al. [106] examined the impact of climate change on farmland values in Bangladesh, finding that increases in temperature reduce smallholder farmland values, while precipitation in both seasons boosts them. The impact varies temporally and spatially, with regions like the Old Brahmaputra River and Young Meghna Estuarine floodplains being particularly vulnerable. The study forecasts moderate reductions in farmland value (8–10 percent) from 2021 to 2060, increasing to 18–24 percent from 2061 to 2100. Additionally, Berhane [73] predicts a 5–8 percent increase in arid and semiarid land in Africa by 2080, indicating heightened desertification due to climate change.

The existing literature on the impact of climate change on farmland value is sparse for developing economies, yet it generally indicates that rising temperatures lead to decreased farmland value, while increased precipitation enhances it. The effect is more pronounced for small landholdings compared to large ones. Additionally, there are temporal differences, with the impact expected to be more significant in the long term than in the medium term. Despite some variations, these findings provide a broad understanding of climate change's influence on farmland value across different regions and timeframes.

3.2.3. *Hunger, undernourishment, and poverty*

The immediate consequence of the negative impact of climate change on agricultural output is that many hundreds of millions of people, particularly in developing countries that rely on agriculture, risk facing extreme hunger, severe undernourishment, and income reductions. Rising agricultural prices due to climate-induced scarcity will also disproportionately affect the poor, who spend the bulk of their resources on food. Schmidhuber and Tubiello [64] projected that by 2080, the number of undernourished people will increase by 5–26 percent relative to a no-climate-change scenario. The impact of climate change may drive between 5 million and 170 million additional people worldwide into severe or extreme hunger, considering the different scenarios.

Wiebe et al. [70] projected the impact of climate change on hunger, revealing stark implications. In a scenario without climate change, most regions were expected to see a significant reduction in the number of people at risk of hunger by 2050, totaling around 406 million globally. However, under a climate change scenario, this number would increase by 70 million people by 2050. Sub-Saharan Africa would bear the brunt, with over two-thirds of the projected decline in the number of people at risk of hunger lost, and more than 40 million people facing hunger by 2050. Fig. 13 presents projections of the number of people at risk of hunger under both no-climate-change and climate change scenarios for the years 2030 and 2050 across various regions. The figure allows for several deductions: Spatially, developing economies, particularly the Middle East and Africa south of the Sahara, are anticipated to be hardest hit. Moreover, the risk of extreme hunger due to climate change appears more immediate in the medium term compared to the long term, suggesting that climate change could precipitate a significant increase in extreme hunger.

Molotoks et al. [69] assessed the impact of climate change on undernourishment prevalence, comparing scenarios of varying global

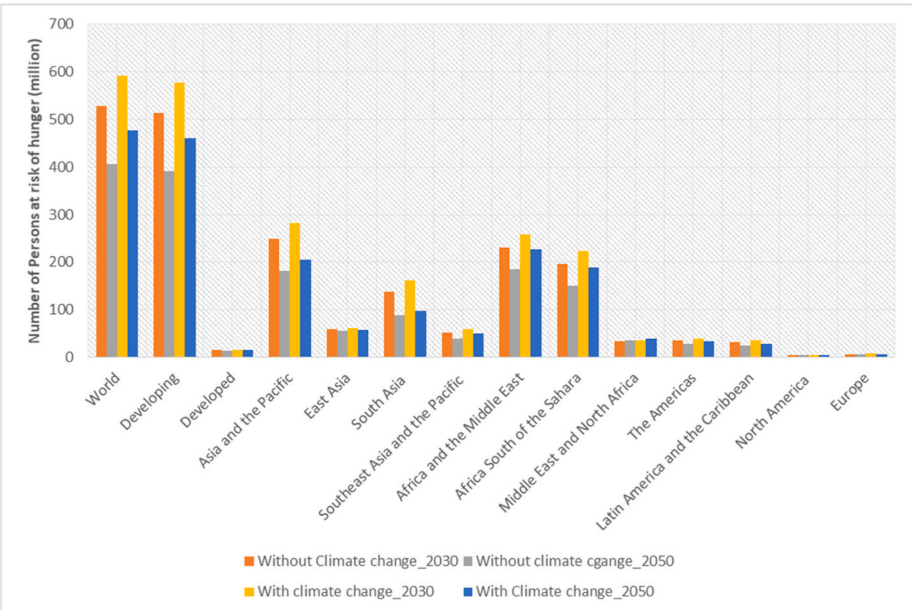

Fig. 13. Projected impact of climate change on the number of people at risk of hunger.
Source: Author's construction using data from Wiebe et al. [70].

impact levels. They found that compared to the baseline, undernourishment prevalence due to climate change more than tripled in both the highest (SSP3-RCP6) and lowest (SSP1-RCP2.6) global impact scenarios, averaging a 13 percent increase over the period. Regions such as Latin America, Africa, and parts of South Asia are expected to face a high prevalence of undernourishment due to climate change. In the lowest global impact scenario, more countries in Africa are likely to experience high prevalence, with significant variability in Latin America and South Asia. Southern Africa exhibited the most drastic difference between the lowest and highest global impact scenarios, with a shift from "moderately low" to "very high" impact resulting in over a 30 percent increase in the region's population projected to be undernourished.

Nelson et al. [35] affirmed the adverse impact of climate-induced agricultural productivity decline on child malnourishment. They found that in developing countries, under an optimistic scenario with high economic growth and less severe climate conditions, the number of malnourished children decreases by 45 percent between 2020 and 2050. However, under a pessimistic scenario with low economic growth and more severe climate conditions, malnourishment only declines by 2 percent during the same period. Spatially, the impact varies, with child malnourishment declining by 50 percent in middle-income countries and 37 percent in low-income countries under the optimistic scenario, but increasing by 18 percent in low-income countries under the pessimistic scenario. The study highlights that children in poor developing economies are likely to suffer more severely from undernourishment due to climate change. The authors suggest that productivity-enhancing measures like improving irrigation efficiency could mitigate child malnourishment, estimating that a 15 percent increase in irrigation efficiency could reduce malnourishment by 0.3 percent in middle-income countries and 0.2 percent in low-income countries by 2050.

Climate change's adverse effects extend beyond hunger and malnourishment to encompass significant income losses due to reduced agricultural output. Numerous studies have explored how climate change affects farm or crop revenues, thereby influencing poverty levels. Seo and Mendelshon [100] examined the impact of climate change on welfare in Latin America under severe, less severe, and moderate climate scenarios. They projected significant income losses for Chilean farmers, with an average loss of 20 percent by 2060 and 53 percent by 2100 under the severe scenario. Both large and small farms are vulnerable to climate change, with smallholder farmers facing higher vulnerability under high temperature conditions and large farms under increased rainfall. Specifically, smallholder farmers are projected to lose 24.1 percent of net revenue by 2060 and 44.3 percent by 2100, while large farms could lose 18.2 percent and 66.3 percent by the same years, respectively. Several potential biases may affect these estimates. Firstly, utilizing a cross-sectional approach renders the model susceptible to omitted variable bias. Secondly, the omission of carbon dioxide fertilization effects, anticipated to boost productivity, could skew results. Lastly, the cross-sectional method's weakness in addressing temporal variation, such as price fluctuations and forthcoming technological advancements, may impact the accuracy of projections.

Hertel et al. [21] explored the poverty ramifications of climate-induced crop yield alterations by 2030, while also considering carbon dioxide fertilization effects. They found that poverty impacts were influenced not only by agricultural changes but also by the income sources of impoverished households. In some regions of Africa and Asia, poverty rates in nonagricultural households could increase by 20–50 percent due to these changes, contrasting with significant declines in poverty for agriculture-specialized households in other parts of Asia and Latin America. This underscores the necessity of examining beyond mere yield changes to understand the broad distributional effects on poverty within and across countries.

Solomon et al. [94] project that climate change will disproportionately affect the incomes and consumption patterns of impoverished rural households compared to urban nonfarming households. They estimate a substantial decline in incomes for both poor and nonpoor rural residents, with reductions of 20.4 percent and 20.8 percent, respectively, by 2050. Similarly, poor urban residents are expected to experience a 20 percent reduction, while nonpoor urban residents will see an 18.2 percent decrease by the same year. In moisture-sufficient highland cereal-based areas, income from labor, land, and livestock is anticipated to decline by 5.1 percent, 8.8 percent, and 15.2 percent, respectively, by 2050. Moreover, climate change is forecasted to severely impact incomes in drought-prone regions, leading to a 40.1 percent reduction for poor rural residents and a 26.8 percent reduction for nonpoor rural residents by 2050. These findings underscore the heterogeneous nature of climate change's impact on household income, even within the same country with varying agricultural ecological zones. Studies like those by Ochieng et al. [107], Kabubo-Mariara and Karanja [108], and Eid et al. [109] further demonstrate the adverse effects of climate change on net revenue, particularly evident in regions like Kenya and Egypt, where simulations indicate significant crop revenue losses ranging between 28 percent and 69 percent across various climate change scenarios. Ochieng et al. [107] conducted a study assessing the impact of climate change on crop revenue in Kenya. Their regression analysis revealed that temperature negatively affects total crop revenue and maize revenue, but positively influences tea revenue. In contrast, rainfall positively affects revenues from all crops and maize but not tea. With a 1 °C temperature increase, crop revenue was projected to decrease by 14.2 percent by 2020, with losses increasing to 14.8 percent by 2030 and 15.2 percent by 2040 as global warming intensifies. However, tea revenue showed an opposite trend, increasing by 2.3 percent in 2020, 2.4 percent in 2030, and 2.5 percent in 2040. Rainfall was projected to boost revenues for all crops by 0.8 percent in 2020, 0.9 percent in 2030, and 1 percent in 2040, while reducing tea revenue by 2.5 percent, 5.5 percent, and 8.8 percent for the same periods, respectively. These findings corroborate those of Eid et al. [109] in Egypt, who found that global warming of 1.5 °C and 3.6 °C reduces net revenue by US$116.67 and US$280.01 per hectare, respectively. Eid et al. suggested that adaptation measures such as irrigation could mitigate the negative impact of climate change, estimating that irrigation would increase net revenues by US$39.26 and US$94.21 per hectare for 1.5 °C and 3.6 °C warming, respectively, compared to nonirrigated crops.

The above studies underscore the profound influence of climate change on hunger rates, undernourishment, and incomes, with research findings offering conclusive evidence of increasing hunger under climate change scenarios, with millions of people at risk of severe or extreme hunger by 2050. However, disparities are evident both spatially and temporally. Developing nations are anticipated to bear a heavier burden, with a larger portion of their populations at risk of hunger, undernourishment, and reduced incomes compared to developed countries. Moreover, the impact is expected to intensify over the medium to long term rather than being immediately felt. The evidence highlights the critical importance of implementing adaptation measures and policies to mitigate these adverse impacts. However, the research also underscores the need for further investigation, particularly in developing economies, to better understand the complex dynamics of climate change's effects on agricultural output, livelihoods, and food security.

3.3. Impact of climate change on water resources

Water resources are used in various areas of the economy, society, and environment [110]. This means that the management of water resources is critical for achieving sustainable development. A significant proportion of the world's population suffers from severe water shortages. Currently, about 3.6 billion people in the world face inadequate access to water resources at least a month per year, and by 2050 this number is expected to rise to 5 billion people [111]. The impact of climate change on hydrological cycles [112] is likely to create a greater need for water as surface and groundwater levels diminish over time. Globally, hydrological cycles are shifting, creating drier days, severe floods, erratic rainfall patterns, and accelerated melting of glaciers [111,112]. More areas of the world recorded drier than normal conditions in 2021 compared with the average of the 30-year hydrological base period [111].

In the same year, 2021, areas such as India and China experienced severe floods, with numerous casualties. Tropical cyclones also affected areas such as Mozambique, Indonesia, and the Philippines [111]. Areas such as Ethiopia, Kenya, and Somalia faced below-average rainfall, which caused severe drought in these economies in 2021. Also in Africa, rivers such as the Nile, Niger, and Congo experienced less than normal discharge in 2021 [111]. In addition, terrestrial water storage was below normal in central parts of South America, North Africa, Patagonia, Madagascar, Central Asia, the Middle East, Pakistan, and North India and above normal in areas such as the central part of Africa, the northern part of South America, and the northern part of China [111].

This section reviews the future trends of climate change's impact on water resources from a developing country perspective, with some bias toward Africa.

Arnell [110] analyzed the expected impact of global warming on global water resources. The findings suggest that average runoff is likely to increase in high latitudes in equatorial Africa, Asia, and Southeast Asia but is expected to decline in mid-latitudes and most subtropical regions. Increasing temperature leads to a general reduction in the proportion of precipitation falling as snow. This is likely to lead to a subsequent reduction in the duration of snowfall in many areas of the world. Therefore, stream flows, including their timing, in such regions would be negatively affected. The study estimates that the number of people suffering from water stress is likely to increase by 53 million people by 2025 under the climate change scenario of the Hadley Centre Coupled Model version 2 (HadCM2), relative to the no-climate-change scenario. Although this number is expected to fall by 2050 under the HadCM2 climate scenario, it would rise to 56 million people under the updated HadCM3 climate scenario. The problem of water stress will be exacerbated in areas such as the Middle East, the Mediterranean, parts of Europe, and southern Africa. The spatial and temporal variations in the impact of climate change on water resources are also highlighted in regional and country-specific case studies.

Studies in Asia, the Middle East, and South America also point to the negative effect of climate change on water resources [113–115]. Hashemi et al. [113] conducted a study to assess the impacts of climate change on groundwater recharge and adaptation in arid areas of Iran. They reported that groundwater recharge modeling showed no significant difference between present and future recharge in all scenarios. De Moura et al. [114] conducted a study on the hydrological impacts of climate change in a well-preserved upland watershed in Brazil. They reported that a well-preserved upland watershed in a subtropical region might be capable of maintaining water availability at a level that is sufficient for human activities in the future, even with the reduction of minimum permit discharge, which is supported by the increase of maximum and medium monthly discharges and a stable flow-duration curve. They further noted that the flow-duration curves in the future will be more affected under the RCP8.5 scenario than under the RCP4.5 scenario, and the variations are very time-dependent. This indicates that severe climate change is expected to affect the future flow of water resources in Brazil, which could push more people into water stress.

Mandal et al. [115] conducted a study assessing climate change and its impact on the hydrological regimes and biomass yield of a tropical river basin in India. They reported that a 14–36 percent increase in precipitation increases the runoff by 39.7–104.1 percent. Compared with the 1950–2000 period a range of 100 percent and 200 percent in monsoon runoff is expected during 2030 and 2080, respectively. Projections of expected runoff volumes in the medium and long term reflect a higher degree of uncertainty. There is evidence of a significant rise in monsoon season runoff for the intra-RCP scenario only during 2070 and 2080. Potential evapotranspiration and actual evapotranspiration are predicted to increase by 2.2–12.7 percent and 1.0–9.0 percent, respectively, compared to a no-climate-change scenario, during the monsoon. The rise in precipitation due to climate change in monsoon areas suggests a rising risk of flooding as well as changes in the quantum of other hydrological fluxes. Based on the simulation output, the climate-driven increase in the volume of water in the basin is expected to cause a 2–3 percent decrease in the output of biomass.

Kundu et al. [116] and Mishra and Lilhare [117] confirm the rise in precipitation during the monsoon in India. Under the RCP 4.5 (8.5) scenario, Kundu et al. [116] predicted a 17–26 percent rise in monsoon season precipitation, whereas Mishra and Lilhare [117] predicted an increase of 50 percent in monsoon season precipitation across the rivers of India, except for the Ganga and Indus basins compared to no warming scenario. Sinha et al. [118] assessed the impacts of climate change on surface runoff in a humid tropical river basin in the Western Ghats in India, assuming land use in 2000 to be constant. They projected that for the climate change scenarios assessed, mean annual surface runoff in the near (2011–2040), medium (2041–2070), and long term (2071–2099) would decrease. However, the decline is expected to be more negative in the near term than in the medium and long term under both RCP4.5 and RCP8.5. The decline in surface runoff is due to a predicted decline in rainfall of 10 percent, 4.14 percent, and 4.98 percent under the RCP4.5 and 11 percent, 4.6 percent, and 5.5 percent under the RCP8.5 scenarios, respectively for the three periods compared with the baseline period (1981–2010). The combined effects of changes in land use and climate showed that surface runoff will increase between January and May but decline from June to December, which may reflect the shift in rainfall from monsoon months to non-monsoon months. The decline in surface runoff from June to December indicates that during these months, irrigation schemes may suffer due to insufficient water storage. However, the increase in surface runoff during the winter and summer signals high flood risk.

Similarly, Kaini et al. [119] studied the impacts of climate change on irrigation water demand, grain yield, and biomass yield of winter wheat in Nepal. They reported that farmers applied only 25 percent of the irrigation water required to achieve the maximum potential grain yield. Irrigation water demand is likely to increase under the RCP4.5 scenario (by 3 percent) but likely to decrease under RCP8.5 (by 8 percent) due to truncated crop duration and lower-maturity biomass by the end of the 21st century. In China, Xiong et al. [120] simulated the effect of climate change on future water availability and found limited impact. Water availability for agricultural purposes declines in southern China but remains stable in northern China. The combined effects of climate change and socioeconomic development produce a reduction in future irrigated areas. Generally, the agriculture sector is likely to face severe water shortages due to competition for water for nonagriculture purposes and the effects of climate change.

The negative impacts of climate change on water resources have also been highlighted in Africa. Coulibaly et al. [121] assessed the impact of climate change on water resource availability in a transboundary basin in West Africa. For the RCP4.5 scenario, their model predicts an overall decline in monthly precipitation compared to the baseline until 2070 and then a slight recovery in 2090. The RCP8.5 scenario predicts a shortened rainfall pattern and a lengthened dry season. In terms of annual rainfall, their model predicts that for both scenarios, annual rainfall will decline, with the worst case occurring under the RCP8.5 scenario. This indicates that climate change is likely to create a serious water shortage in West Africa. This result somewhat corroborates the findings of op de Hipt et al. [122]. The authors found that in West Africa under the RCP4.5 scenario, climate change will increase precipitation by 50 percent. However, under the RCP8.5 scenario, climate change will decrease precipitation by 10.9 percent. In terms of the impact of climate change on river discharge, Coulibaly et al. [121] showed a negative impact until 2100 for both scenarios, compared to the baseline (1961–1980). For the RCP 4.5 scenario, the observed values vary from −1.2 percent in 2030 to −2.3 percent in 2070 and -2.1 percent in 2090. Under the RCP8.5 scenario, the researchers saw changes in river discharge varying from +4.2 percent to −7.9 percent in 2030 and 2090, respectively. This confirms the results of Andersson et al. [123] in a study assessing the climate change implications for water flow along the Okavango River in southern Africa. The annual water flows for 2050–2080 and 2070–2099 show a decline of 14–20 percent and 17–26 percent, respectively, for all climate change scenarios. The authors found that the simulated impact of climate change on monthly water flow was proportionally higher than the impact on annual mean water flow.

Soro et al. [124] assessed the impact of climate change on water resources in the Bandama basin in Côte d'Ivoire. The monthly rainfall may decrease from December to April. During this period, it is projected to decrease by 3–42 percent at all horizons (2006–2035, 2041–2060, and 2066–2085) under RCP4.5 and by 5–47 percent under RCP8.5. These variations suggest a reduction in surface and groundwater resources.

In addition, Ogallo et al. [125] conducted a study on climate change projections and the associated potential impacts for Somalia. They reported a trend of decreasing rainfall leading up to 2030, followed by an increase in rainfall by 2050 and 2070.

Hamududu and Ngoma [126] conducted a study on the impacts of climate change on water resource availability in Zambia. They reported that the temperature is projected to increase by 1.9 °C and 2.3 °C by 2050 and 2100, respectively, in Zambia. Rainfall is projected to decrease by approximately 3 percent by mid-century but only marginally, by approximately 0.6 percent, by the end of the century across the country. These changes in rainfall and temperature will decrease water availability by 13 percent by 2100 at the national level. At the river basin level, the northern basins are projected to remain the same or experience slight gains in water resources compared with those in the southern and western parts of Zambia, where reductions of up to 9 percent are projected. In particular, the Zambezi, Kafue, and Luangwa River basins are projected to have fewer water resources due to reduced rainfall and higher temperatures.

Boojhawon and Surroop [127] conducted a study on the impact of climate change on the vulnerability of freshwater resources in Mauritius. They reported that for the period 2020–2050 under a business-as-usual scenario, the freshwater sector remained in a state of moderate vulnerability. Under the effects of climate change, this shifted to high vulnerability. The findings indicate that the country is likely to enter water scarcity (water availability of less than 1000 cubic meters per capita) by 2030 and face overexploitation of water resources (a water exploitation rate greater than 100 percent) by 2040.

Other studies such as Githui et al. [128] and Balcha et al. [129] downplay the effect of climate change on rainfall patterns. Githui et al. [128] examined the future implications of climate change on the Nzoia catchment in the Lake Victoria basin and how it might influence future stream flow in Kenya. Using the soil and water assessment models, they found increased amounts of rainfall but with monthly variation. Generally, rainfall is predicted to be higher in the 2050s than in the 2020s. In terms of the impact of climate change, the study found that a change in annual rainfall between 2.4 and 23.2 percent will trigger a change in stream flow of 6–115 percent. Holding other factors constant, a significant increase in stream flow is expected due to the rise in rainfall amounts in the future. Regarding the temperature and stream flow relationship, the study found that stream flow is not very sensitive to changes in temperature.

Balcha et al. [129] conducted a study assessing the future impact of climate change on water balance components in the Central Rift Valley lakes basin in Ethiopia. They reported that future annual and seasonal rainfall will show increasing and decreasing trends, but they are statistically insignificant. Furthermore, future temperatures in the subbasins show a significant increase. For the applied scenarios, an increasing and decreasing trend of future rainfall and increased temperatures would decrease the water yield by 4.9–15.3 percent in the Katar subbasin and 6.7–7.4 percent in the Meki subbasin. Furthermore, annual water yields will increase in the range of 0.38–57.1 percent and 6.57–49.9 percent for the Katar and Meki subbasins, respectively. The researchers further noted that rainfall and temperatures in the study region are anticipated to increase by 2040 and 2070 under both the RCP4.5 and RCP8.5 climate scenarios.

The review highlights the intricate and often inconclusive impact of climate change on water resources. Studies highlight both adverse and mitigating impacts of climate change on water resources. While some regions risk facing dwindling water availability, others might exhibit resilience or even potential gains. In Asia, particularly in India, rising precipitation levels due to climate change could heighten flood risks, while reducing surface runoff threatens irrigation schemes. In China and Nepal, climate change may affect future irrigated areas, with risks exacerbating under severe scenarios. In Africa, the situation is complex. Climate change is anticipated to decrease rainfall, surface runoff, and groundwater, with mixed impacts under less severe scenarios. However, under very severe scenarios, there is consensus on significant water resource reduction. Notwithstanding, concerns persist that even in milder scenarios, African countries could face water scarcity without appropriate adaptation efforts.

Research on climate-water dynamics emphasizes the need for nuanced approaches tailored to regional contexts. However, the complexity of these interactions underscores the necessity of adaptive strategies informed by robust scientific assessments. Future research should focus on bridging knowledge gaps, particularly in regions underserved by existing studies. Specifically, studies should delve into the efficiency and efficacy of various adaptation measures, such as sustainable water management practices and irrigation innovations which are critical for enhancing resilience against climate-induced water stress. Additionally, more research is needed to understand the complex intricate linkages between climate, water resources and socioeconomic factors to guide informed decision-making for a water-secure future.

3.4. Impact of climate change on health

Climate change is known to be linked to multiple health issues, including respiratory diseases, heart disease and stroke, water- and food-related illnesses, poor mental health, and pest-related diseases. Climate health damages are projected to be between US$2 billion and US$4 billion globally by 2030. Between 2030 and 2050, approximately 250,000 people are expected to die from climate change–related health issues such as malnutrition, malaria, heat stress, and diarrhea [130]. Developing countries with weak health systems and infrastructure will suffer the most from the health effects of climate change. Studies on climate change effects have looked at the future health implications of climate change with varied outcomes in terms of the degree of impact. Notwithstanding the varying degrees of impact, there is some collective agreement within the literature on the possible negative effects that climate change could have on future health outcomes.

Li et al. [131] conducted a study that sought to forecast future climate change impacts on heat-related mortality in large urban areas in China. They projected that for the 20 years of 2041–2060, relative to 1970–2000, the incidence of excess heat-related deaths annually in the 51 cities studied will be approximately 37,800, 31,700, and 25,800 under the RCP8.5, RCP4.5, and RCP2.6 scenarios, respectively, for the period 2041–2060. Slowing climate change by achieving the low-emission scenario, RCP2.6, relative to RCP8.5, was estimated to avoid 12,900 the number of deaths per year in the 51 cities will decrease by 12,900 in 2050s and by 35,100 in 2070s. The highest mortality risk is concentrated in cities located in the northern, eastern, and central regions of China.

Aboubakri et al. [132] conducted a study that sought to project the mortality attributed to heat and cold and the impact of climate change in Kerman, a dry region of Iran. They reported the effect of climate change on mortality while considering adaptation. The models showed that the mean temperature will rise by 1 °C by 2050 in all scenarios in Kerman. Correspondingly, heat-related mortality will rise in the future, whereas cold-related mortality might slightly decrease. There was significant uncertainty around cold-related deaths.

Chang et al. [133] conducted a study on the impacts of climate change on health and labor force participation in Taiwan. They projected that a 1 °C increase in average summer and winter temperature, and variation in temperature are associated with a 2.9 percent, 1.3 percent, and 14.3 percent rise in the number of cardiovascular disease (CVD) deaths, respectively. The study predicts an additional 4200–4500 deaths from CVD (including 900–1000 deaths among the labor force) per annum from 2021 to 2040, which is likely to rise to 5600–6300 CVD deaths. These findings suggest an increase in both the mortality and morbidity of CVD due to climate change. Consequently, on the expenditure side, increasing the average summer and winter temperatures by 1 °C could be associated with 1.37 percent and 0.47 percent increases in CVD-related health expenditures, respectively. In contrast, raising annual precipitation by 1 percent is associated with a 0.08 percent decrease in CVD-related health expenditures.

Climate change is also expected to increase disease incidence in the future. Ermert et al. [134] studied the impact of regional climate change on malaria risk due to radiative forcing and land-use changes in tropical Africa. They reported that the likelihood of malaria epidemics is projected to increase in the southern part of the Sahel compared with a no-warming scenario. In most East African countries, the intensity of malaria transmission is expected to increase. Projections indicate that malaria will become endemic in highland areas that were formerly unsuitable for transmission, whereas in the lower-altitude regions of the East African highlands, epidemic risk will decrease. In addition, climate changes driven by greenhouse gases and land-use changes will significantly affect the spread of malaria in tropical Africa well before 2050. The geographic distribution of areas where malaria is endemic may be significantly altered in the coming decades.

Shiravand et al. [135] conducted a study on the effects of climate change on the potential distribution of the main vector and reservoir host of zoonotic cutaneous leishmaniasis in Yadz Province in central Iran. They projected that with both scenarios (RCP 4.5 and RCP 8.5) in 2030 and 2050, the mean temperature of the wettest quarter and the annual temperature range had the greatest effect on the model for the vector and reservoir hosts, respectively. There are spatial variations in the impact, however. While it is predicted that the presence of the vector will increase in the western part, the reservoir will increase in the northern and central parts of the province. Iwamura et al. [136] conducted a study on the accelerating invasion potential of the disease vector *Aedes aegypti*, the yellow fever mosquito, under climate change. They reported that from 1950 to 2000, the world became approximately 1.5 percent more suitable per decade for the development of *Aedes aegypti*, and this trend is predicted to accelerate to 3.2–4.4 percent per decade by 2050. Invasion fronts in North America and China are projected to accelerate from 2 to 6 km per year by 2050. An increase in peak life cycle completion combined with extended periods suitable for mosquito development was simulated to accelerate the vector's global invasion potential.

These studies reveal the negative impact of climate change on health, with spatial and temporal variations. As indicated, the effects of climate change on health are likely to be larger in the long term than in the short term. In addition, countries with weak health systems are likely to suffer more from the impact of climate change on health.

Due to the close connection between health and productivity, the negative effects of climate change on health could have negative implications for the growth of economies, particularly those in developing countries. Without climate mitigation intervention, the future effects of climate change could erode any positive gains achieved in health and hence derail efforts targeted at achieving sustainable development. Limiting global warming to within the 1.5 °C limit could help protect millions of people from disease and death.

Transitioning to low-carbon technologies to reduce global warming also has positive impacts on health, thanks to these technologies' lower emissions of local pollutants. For example, West et al. [137] studied the co-benefits of mitigating global greenhouse gas emissions for future air quality and human health. They reported that relative to a reference scenario, mitigating global greenhouse gas could prevent 0.5 ± 0.2 million, 1.3 ± 0.5 million, and 2.2 ± 0.8 million premature deaths in 2030, 2050, and 2100, respectively. The estimated global average marginal co-benefits of avoided mortality are US$50–380 per tonne of carbon dioxide. This is higher than the marginal abatement costs in 2030 and 2050 but within the low range of costs in 2100. It is estimated that East Asian co-benefits could be 10–70 times larger than the marginal cost in 2030.

Cai et al. [138] conducted a *Lancet* Countdown study on the fine particulate matter ($PM_{2.5}$) pollution-related health impacts of China's projected carbon dioxide mitigation in the electric power generation sector under the Paris Agreement. The results showed that due to the more carbon-intensive nature of the energy sector, northwest China stands the risk of experiencing higher implementation costs and premature death than business as usual. By 2030, the air quality in northwest China (particularly in Gansu, Shaanxi, and Xinjiang provinces) will become worse and this is expected to cause more than 10,000 premature deaths in these areas, but this is expected to fall by 2050.

Dimitrova et al. [139] conducted a study projecting the impact of air pollution on child stunting in India, examining synergies and trade-offs between climate change mitigation, ambient air quality control, and clean cooking access. They reported that reductions in ambient air pollution under the 2 °C Paris Agreement target positively influence the growth of children but climate change is likely to offset this positive effect through reduced access to clean cooking. Controlling ambient air pollution and subsidizing access to clean cooking could create a net benefit of 2.8–6.5 million prevented cases of child stunting between 2020 and 2050 compared with the business-as-usual scenario, with the greatest benefit falling on the most disadvantaged children and geographic regions.

The review above highlights the sparse nature of literature investigating the nexus between climate change and health outcomes, particularly in high-risk areas such as Africa. Nevertheless, the existing literature generally paints a gloomy picture for the global health system due to climate change effects, with more serious implications in areas with very poor health systems. To address equity concerns and foster resilience, it is crucial to explore the social determinants of climate-induced health risks. This is an area where the literature is notably lacking. Additionally, understanding the co-benefits of low-carbon technologies on the environment and health can yield synergistic benefits, offering a win-win situation for environmental sustainability and public health.

3.5. *Impact of climate change on energy security*

UN SDG 7 aims to "ensure access to affordable, reliable, sustainable, and modern energy for all" by 2030. This goal was established to help address the energy poverty problem, which is considerable among the developing countries of the world. While some gains have been made, climate change could erode the initial advances, as it affects both energy demand and supply [7]. The energy system is vulnerable to a variety of climate change impacts, such as hurricanes, heat waves, wildfires, extreme weather, rising temperatures, and heavy rainfall [140]. However, as these climate change events vary by location, the impact of climate change on the energy system is context dependent. Because most developing countries already face the challenge of poor and weak energy infrastructure, their energy systems are expected to be more vulnerable to climate change events than those of developed economies. Yalew et al. [39] analyzed more than 200 studies that estimated the future impacts of climate change on the energy systems of global and regional economies. These studies predict a reduction in hydropower and thermal energy capacity, a rise in cooling demand, and a decrease in heating demand. At the regional level, the results look mixed and inconclusive, but the greatest impact of climate change on the energy system is likely to occur in Latin America and South Asia. In a similar literature review of climate change's impact on the energy supply, Cronin et al. [37] note that while there is some consensus regarding the expected impact of climate change on some energy sources, such as wind, solar, and thermal, the impact projections vary for hydropower and bioenergy sources.

Some studies have reported the impact of climate change on energy demand and supply in a developing country context. Mei et al. [141] conducted a study analyzing the impact of climate change on the energy–economy–carbon nexus in China. They projected that the national electricity demand would grow by around 58.6 percent in the next 30 years under climate change, compared with the no-climate-change scenario. The growth in energy demand associated with climate change was confirmed in a review study by Tahir and Al-Ghamdi [20], who concluded that climate change increases energy requirements in the built environment. This was also confirmed by Campagna and Fioriti [142] and Li et al. [38]. Li et al., however, note that the greatest impact occurs in the summer and warmer winter periods.

In the case of the power generation potential of solar photovoltaics (PV), Dutta et al. [143] quantified the change in global solar PV power generation potential under climate change as ranging from −10 percent to +10 percent, depending on the SSP scenario. They noted that the increase in cloud coverage will reduce solar radiation and hence the power generation potential in Asia. Niu et al. [144]

confirmed this in China when they assessed the power generation potential of solar PV under climate change scenarios. They noted that if global warming is limited to 1.5 °C by 2100, solar PV power generation potential will rise by 1.36–5.90 Wm^{-2}. However, failure to achieve this global warming target will reduce the power generation potential of solar PV. Under SSP5-RCP8.5, the authors predicted that solar PV power generation potential will decrease from 192.71 Wm^{-2} to 189.96 Wm^{-2} in 2023–2100. Among the factors contributing to the reduced power generation potential for Solar PV, they note that solar radiation alone will be responsible for more than 50 percent, whereas aerosols and cloud cover would be responsible for about 20 percent.

In the case of wind power generation potential, Zhou et al. [145] projected that under the SSP5-RCP8.5 climate scenario, average wind speed will fall by 40 percent, which would reduce wind power generation, particularly in northern China. Meanwhile, in the south of China, the authors found the potential of wind power generation to increase due to a predicted 2 percent increase in wind speed.

In Africa, studies have also confirmed the potential negative effects of climate change on power generation. Agbor et al. [146] examined the impact of climate change on solar radiation and the power generation potential of solar PV in West Africa. Generally, they found that climate change might reduce solar radiation and hence reduce the power generation of solar PV in the future under the moderate and worst-case scenarios in 2015–2050 and 2051–2100. However, they noted that the decline depends on the type of solar PV technology adopted. Polycrystalline silicon technology seems to exhibit greater generation potential under both the moderate and best-case scenarios. Under the worst-case scenario, amorphous silicon technology produces a less than 1 percent increase in solar PV output, whereas the remaining technology (i.e., mono-crystalline, poly-crystalline, HIT hybrid silicon, cadmium telluride thin film, and indium gallium diselenide thin film) exhibits a less than 1 percent decline in solar PV output. Other regional studies on solar PV potential generally predict a decrease of 10 percent in solar generation by the end of the century [147–149].

Regarding the global impact of climate change on hydropower potential, the research results are not conclusive. While some studies predict minimal impacts [150,151], others suggest a 6.5 percent decline under RCP8.5 by 2080 [152,153]. Bombelli et al. [154] revealed that variability in cloud coverage, temperature, and precipitation could negatively impact the power generation potential of some hydropower sites in East Africa. Mirani et al. [155] conducted a study on the evaluation of hydropower generation and reservoir operation under climate change in the Kesem Reservoir in Ethiopia. They reported that future climate scenarios predicted increasing and decreasing trends in temperature and precipitation, respectively. Under the RCP4.5 climate scenario, average energy generation is likely to decrease by 0.64 percent and 0.82 percent in the short term (2021–2050) and the long term (2051–2080), respectively. In the case of the RCP8.5 climate scenario, average energy generation will decrease by 1.06 percent and 1.35 percent in the short and long term, respectively. Comparatively, the reduction in energy generation was higher in the RCP8.5 scenario than in the RCP4.5 scenario. This indicates that there will be high energy fluctuations and a decreasing trend in future energy generation if global warming is not contained. In addition, the hydropower potential of the Zambezi River basin in Africa is predicted to decrease by 10 percent by 2030 and 35 percent by 2050 due to climate change [7].

Fant et al. [156] predict that climate change will have no significant impact on hydropower resources in southern Africa. The lack of consensus on the impact of climate change on hydropower generation potential is also highlighted in other local-level studies. For example, while van Vliet, van Beek et al. [152] project a 5.2 percent increase in hydropower potential in high-latitude areas, which is also confirmed by van Vliet, Wiberg et al. [153], Hamududu and Killingtveit [150] project a plus or minus 1 percent change in hydropower generation potential under different climate scenarios.

The following can be deduced from the above discussion on the impact of climate change on energy systems. Climate change may pose a significant threat to energy security in developing countries, particularly concerning the demand side of the energy sector. However, on the supply side, the situation is less clear. While there is some consensus regarding certain energy sources, others remain shrouded in uncertainty. Generally, the evidence points to a small impact on the supply side, but the effect varies by location and energy source, with some large effects occurring in specific places and with particular energy sources. More research is needed to understand how climate change impacts specific energy sources.

Given the context-specific vulnerabilities and opportunities, more localized impact studies of climate change on energy systems are needed to develop tailored strategies to enhance energy system resilience and mitigate the adverse effects of climate change. Moreover, a simultaneous understanding of how climate change impacts both supply and demand in energy systems is critical for identifying areas of synergy and trade-offs.

Developing economies, such as those in Africa, are likely to suffer the most from the adverse effects of climate change. With energy poverty on the rise in Africa, one immediate benefit of limiting global warming to below 2 °C could be a reduction in energy poverty, which is linked to other socioeconomic factors such as health, education, income, and gender equality. Therefore, it is important to understand the socioeconomic implications of climate-induced changes in energy systems, such as how the impact of climate change on energy access influences health outcomes, livelihoods, and education. The literature is limited in assessing how energy innovations such as energy storage, renewable energy investments, and grid modernization can moderate the negative impact of climate change on energy systems.

Lastly, more research is needed to understand how to integrate climate adaptation and mitigation into general energy planning and policy frameworks. This integration could be critical to achieving the twin goals of sustainable energy for all and environmental sustainability.

4. Conclusion

This study reviews the patterns and trends of the impact of climate change on socioeconomic indicators, including economic growth, agricultural productivity, poverty, food security, health, water resources, and the energy sector. The data originate from previously published works that provide a quantitative assessment of the future impacts of climate change on socioeconomic factors. Different aspects of these factors have been examined in the literature independently by researchers seeking to understand the patterns and trends of climate change effects, but a simultaneous analysis of all these factors is an information gap we noticed in the literature. Because there is considerable consensus around the fact that developing economies, particularly those in Africa, will suffer the most from the risks presented by climate change, this study focuses on developing economies, with some bias toward African economies. While every attempt was made to review all relevant literature, some information could not be included in this work because of issues such as subscription charges. Therefore, we are cautious in claiming that the information presented in this report is exhaustive. The following conclusions emerged from this study.

Regarding the GDP effects of climate change, there are likely to be winners and losers. The literature reveals positive gains for developed economies, but only until the medium term, beyond which the positive gain in GDP begins to diminish. For developing countries, the cost tends to outweigh the benefit even in the medium term, and this tendency increases in the long term. In addition, we note that although the predicted impact of climate change on GDP may be minimal at the global level, it is quite substantial at the subregional and country levels in some cases.

Among the developing regions, Africa is one of the areas that is at most risk from climate change. In Asia, an economic loss of between 1.18 percent and 11 percent of GDP is predicted, while in Africa, the decline in GDP due to climate change ranges from 4 percent to 11 percent in the long term. Studies focusing on Africa reveal a mean and median decline in GDP per capita of 7.12 percent and 4.8 percent, respectively, under global warming, compared to the no-climate-change scenario. Even within Africa, we notice important heterogeneities in the impact of climate change on GDP. Areas in the west and east of Africa are identified as at particularly high risk. Within these areas, Ghana, Togo, Côte d'Ivoire, Mauritius, Malawi, and Mozambique appear to be some of the countries at highest risk over the medium to long term. Generally, both global and regional-level studies project that climate change effects on GDP are likely to be stronger in the long term (2100) than in the medium term (2025–2050). In the case of Africa, the economic loss associated with climate change is projected to be marginal until 2050, when the economic loss is expected to grow. Again, while there is some consensus on a global warming tipping point of below or equal to 2 °C, in Africa there is no consensus on the tipping point, which may have already passed. The negative effect of climate change is felt above 1 °C. The spatial and temporal variations in the impact of climate change on economic growth are also highlighted in subregional and country-level analyses.

Regarding the effects of climate change on the agricultural sector, studies agree that this sector is most vulnerable to the threat of climate change. Food insecurity and loss of farmland value are some of the likely consequences of future global warming patterns in the agricultural sector. There is general agreement that while rising temperatures reduce crop yield and productivity, an increase in precipitation levels will increase crop yield in the future. In the case of the impact on rice yield, the evidence seems conclusive, and major producing countries are likely to suffer more due to climate change. However, in the case of crops such as maize, sorghum, and millet, the evidence appears very scattered, with no definite pattern. Interestingly, both developing and developed economies risk a reduction in crop yield due to climate change. However, the incidence seems greater among developing economies, particularly those in Africa.

Regional-level studies suggest that climate change could cause crop yield changes of between −2.9 percent and −18 percent in Africa, compared to +1 percent and +14 percent for Latin America and −0.6 percent and −10.8 percent for the rest of the world by 2030 and 2050, respectively. Climate change is likely to aggravate food insecurity more in the long term than in the medium term. Crop yield reduction is predicted to range from 2.9 percent to 5 percent by 2030 but from 6.8 percent to 18 percent after 2050. In Africa, West Africa and East Africa are highly risk-prone areas. The type of crop and location play a critical role in how climate change influences crop yield. We note that different crops may exhibit different resilience levels to climate change based on their location. This is true, for example, of maize and sorghum in Africa. This illustrates the role that spatial dynamics play in understanding the effects of climate change on yields. Rainfed crops are likely to be more affected than irrigated crops. The general prediction of lower crop yields in the agricultural sector is expected to cause crop price inflation of 10–100 percent.

The evidence on the impact of climate change on farmland value though limited appears to be very conclusive, with studies predicting a decline in farmland value with rising temperatures and a rise in farmland value with rising precipitation levels. The predicted decline in farmland value is larger for small landholdings than for large landholdings. In addition, we note that the impact is lower in the medium term than in the long term.

The consequence of lower agricultural productivity due to climate change is an increase in the number of people facing extreme hunger, suffering from undernourishment, and generating less income. A significantly larger number of people are likely to suffer from extreme hunger if global warming is not contained. The incidence of this problem is predicted to be higher in developing countries than in developed economies. Among developing economies, Africa is likely to suffer the most from hunger. The literature revealed that more than 200 million people risk experiencing severe hunger due to climate change in Africa in the medium to long term. In addition, future climate change is likely to increase the prevalence of undernourishment, particularly in Asia, Latin America, and Africa. Crop revenues are also at risk due to climate change. Projections show that more than 30 percent of crop revenues could be lost due to climate change in developing countries. As most people in the developing world depend on the agricultural sector for their livelihoods, this indicates that a significant number of people risk being pushed into poverty. The literature estimated that poverty will be 20–30 percent higher in Africa in a climate change scenario compared with a no-climate-change scenario.

Climate change is also affecting the hydrological cycle, altering the quantity, and timing of stream flow as well as groundwater, freshwater, and precipitation levels. These effects are noted across regions and countries but with some degree of heterogeneity. In Asia, the risk of flooding dominates the climate change impact rather than threats to irrigation systems. However, in Africa, the risk of water shortage dominates, and this risk is projected to escalate under severe climate change scenarios. Climate change is likely to push a significant number of people (more than 50 million) into water stress.

The health effects of climate change are also significant, particularly in developing economies. There is general agreement on the role of climate change in increasing disease spread and mortality. The impact depends on the period and severity of climate change. The negative impact of climate change on health is greater under severe climate scenarios than under less severe climate scenarios. In addition, the negative impact on health looks substantial in the long term. Economies with very weak health systems are likely to be hardest hit by climate change. The health damage caused by climate change could exceed US$2 billion by 2030.

Finally, climate change is a threat to energy security, particularly in developing economies. The effect is more obvious on the demand side, where there is general agreement that global warming will increase energy consumption. Regarding the supply side, however, the evidence is mixed and depends on the location and energy source. There is general agreement on the negative effects of climate change on the generation potential of some energy sources, such as solar, wind, and thermal, but there is no consensus on the potential effect of climate on the generation potential of other energy sources, such as hydropower and bioenergy. Particularly for solar energy, the impact of climate change is minimal.

In summary, this review has provided evidence of the effects that climate change could have on a variety of socioeconomic indicators. There will likely be winners and losers, most probably in the medium term, but in the long term, all economies (both developing and developed) might be on the losing end.

5. Implications for future research

Based on the above, we derive the following implications for policy and future research. First, we note that the literature provides varied results in terms of both the spatial and temporal dynamics of the effects of climate change on socioeconomic indicators in developing economies. The underlying reason for this is the varied initial conditions (temperature, wealth, disease burden, sectoral output, etc.), model assumptions, and estimation techniques adopted in these studies. These heterogeneities underscore the important point that there is no one-size-fits-all approach to addressing the future ramifications of climate change. Individualism and context specificity should be high on the global climate policy agenda. Understanding the sources of these spatial and temporal heterogeneities in climate change's effects on economies is essential for designing tailored adaptation and mitigation policies. Unfortunately, research is lacking in this regard.

Second, across all the socioeconomic indicators, the review highlights substantial evidence for economic growth and agricultural production. However, areas such as water, health outcomes, energy systems, hunger, undernourishment, and poverty are underrepresented. Future climate studies should prioritize these areas.

Third, we find that different crops may exhibit varying climate resilience depending on location. This emphasizes the important role that agroecological conditions play in how climate change impacts crop yields. Unfortunately, research investigating the role of agroecological conditions or factors in crop resilience dynamics to climate change is lacking.

Fourth, the evidence of climate change's effects on both energy demand and supply is disjointed, making it difficult to understand the potential synergies and trade-offs. Future research should prioritize examining the effects of climate change on both energy demand and supply simultaneously.

Fifth, many climate-based forecast models do not account for adaptation interventions in sectors such as health and energy. Low-carbon technologies could mitigate the negative impacts of climate change on health. Similarly, in the energy sector, innovations such as energy storage, renewable energy investments, and grid modernization can enhance resilience to climate change effects. Future climate-based forecast models should incorporate these interventions to understand the co-benefits for the environment, public health, and energy systems.

Finally, there is a complex interrelationship among socioeconomic indicators. However, existing climate models do not reflect this reality. Future climate-based forecast studies should prioritize cross-cutting themes such as the social determinants of climate-induced health effects and the socioeconomic implications of climate-induced changes in the energy sector, including how climate change impacts energy access, health, education, and livelihoods.

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Data availability statement

This study is a review study. Materials used for the study cannot be made available due to copyright issues. However, interested readers can consult the original source of the materials for accessibility.

CRediT authorship contribution statement

Philip Kofi Adom: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The author declares that there are no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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