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REVIEW ARTICLE

Climate change and agriculture: A comprehensive review of impacts, adaptation strategies and resilience mechanisms

Kamali S P[1], Premavathi R[1*], Asokhan M[1], Dheebakaran G A[2], Karthikeyan R[3], Gangai Selvi R[4] & Ponsneka I[1]

[1]Department of Agricultural Extension and Rural Sociology, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India
[2]Agro Climate Research Centre, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India
[3]Directorate of Crop Management, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India
[4]Department of Physical Sciences and Information, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India

*Correspondence email - premavathi.r@tnau.ac.in

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Abstract

Climate change poses a profound threat to global agriculture, with far-reaching implications for food security, rural livelihoods and sustainable development. Agriculture remains highly vulnerable to climate-induced stresses such as droughts, heat waves, erratic and intense rainfall, storms, floods and the resurgence of pest and disease outbreaks. These climatic disruptions directly influence crop physiology, soil health, water availability and overall productivity. Projections indicate a substantial rise in temperature and greater variability in rainfall patterns in the coming decades, increasing the frequency and severity of climate extremes. As a result, yields of major staple crops may decline by up to 30 %, primarily due to reduced plant productivity, shortened growing periods and crop failures in climate-sensitive regions. In response to these escalating challenges, the promotion and integration of climate-smart and resilient agricultural practices have become essential to sustaining production systems. Approaches such as climate-smart agriculture (CSA), improved water and soil management, stress-tolerant crop varieties, diversified farming systems and innovative adaptation technologies play a crucial role in enhancing resilience. Strengthening institutional support, extension services and farmer capacities is equally vital for effective adaptation. This scoping review systematically synthesises current evidence on the impacts of climate change on agriculture and identifies a wide range of adaptation and resilience strategies implemented across different agro-ecological contexts. The review also highlights key gaps in existing knowledge and suggests future directions for research and policy to bolster climate-resilient agricultural systems and ensure long-term food security.

Keywords: adaptation strategies; climate change; food security; impacts; sustainable agriculture

Introduction

Climate change is the biggest global issue today. Global warming and increasing greenhouse gas (GHG) emissions have accelerated this (1). Decades of evidence show that major climate shifts are driven by human activities that have changed the Earths' atmosphere (2). The United Nations Framework Convention on Climate Change (UNFCCC) defines climate change as a change in the Earths' climate that goes beyond natural variability over similar time scales. This is either directly or indirectly caused by human activities that alter the planets' atmosphere. So global climate change is changing how we interact with the natural world, turning a stable and predictable climate into an unpredictable and dangerous one (3). Agriculture is highly vulnerable when it comes to climate change - its enormous scale and total dependence on how the weather turns out means the consequences for the economy are going to be huge (4). For instance, shifts in temperature and rainfall patterns really aren't good news for crop yields - the warmer it gets, the harder it is for crops to thrive, but on the flipside, more rain can sometimes help balance out the heat stress and keep things somewhat on track (5). The issue is that climate change affects crops, soils, livestock and even pests in different ways depending on the type of crop, the region its' in and just how much the weather changes. Climate change is predicted to have a huge impact on the entire agriculture sector through a mix of direct and indirect effects on crops and the whole food chain (6). Facing severe consequences, the projections are pretty glum - many parts of the world are expected to see a massive rise in droughts because of climate change, which will see the global area affected jump from 15.4 % today to as high as 44 % by 2100. In areas that are already prone to droughts, even the biggest crops are expected to take a massive hit with a 50 % decline by 2050 and almost 90 % drop by the end of the century (7).

Declining crop yields are likely to elevate food prices and adversely impact global agricultural welfare, with projections indicating an annual reduction of 0.3 % in future global gross domestic product (GDP) by 2100 (8). In contrast, although climate change may have a limited effect on overall global food availability, developing nations are expected to experience severe negative impacts (9). In India, temperature is projected to jump up by 2.33 °C to 4.78 °C while CO_2 levels double and heat waves go on for ages, all of which are a massive threat to the farm sector (10). Just looking at the different ways to tackle this problem, this review will hopefully give a solid grasp of the ever-changing picture of how people are adapting to and coping with climate change.

Materials and Methods

This comprehensive review employed a structured approach to identify, select and synthesise literature on the impacts of climate change on agriculture, adaptation strategies and resilience mechanisms. Relevant peer-reviewed articles, reports and review papers published between 1998 and 2025 were retrieved from major scientific databases, including Scopus, Web of Science and Google Scholar. A combination of keywords such as "climate change", "agriculture", "climate-smart practices", "adaptation strategies", "resilience" and "sustainability" was used to refine the search. Studies were included if they addressed climate-induced impacts on crop production, livestock, fisheries, or natural resources and if they discussed adaptation or resilience-building measures. Publications lacking empirical or conceptual relevance were excluded. The selected literature was systematically analysed to identify common themes, evidence gaps and emerging trends, enabling a comprehensive synthesis of current knowledge across diverse agro-ecological contexts.

Impacts of Climate Change on Agriculture and Allied Sectors

The shifting climate is the major factor affecting agricultural production and global food security (11). Over recent years, the distribution and seasonal behaviour of various plant and animal species have changed because of climate variability. The effects of climate change are more pronounced in semi-arid and arid regions (12). In several regions of Asia, crop productivity has significantly declined due to decreased availability of timely water and rainfall, as well as increasingly erratic and intense rainfall patterns observed in recent decades (13). In agricultural economies like India, climate change poses a threat to both food security and economic development (14). In particular, the agricultural sector is regarded as the most vulnerable to climate change (15). The negative impact of climatic factors on crop yields is likely to have serious consequences for food and nutritional security (16). Climate variability accounts for nearly 60 % of variation in crop yields, making it a critical factor affecting food production and farmers' incomes (17). In addition to its effects on crop yields and production, climate change also creates impacts on essential natural resources, particularly land and water, which are crucial for agriculture. Climate change leads to extreme weather events, sudden onset of disasters and new vectors for human and livestock diseases, with many of these hazards interacting with each other (18). The adverse effects of climate variability and change have compelled rural households in highly vulnerable areas to migrate seasonally or permanently (19).

Fig. 1 highlights the key impacts of climate change on the agricultural sector, demonstrating how climate-induced stresses can lead to reduced harvests and diminished income sources for vulnerable farming communities. Most studies show that climate change has a statistically significant and negative impact on agriculture and other sectors of the economy (20). A study found

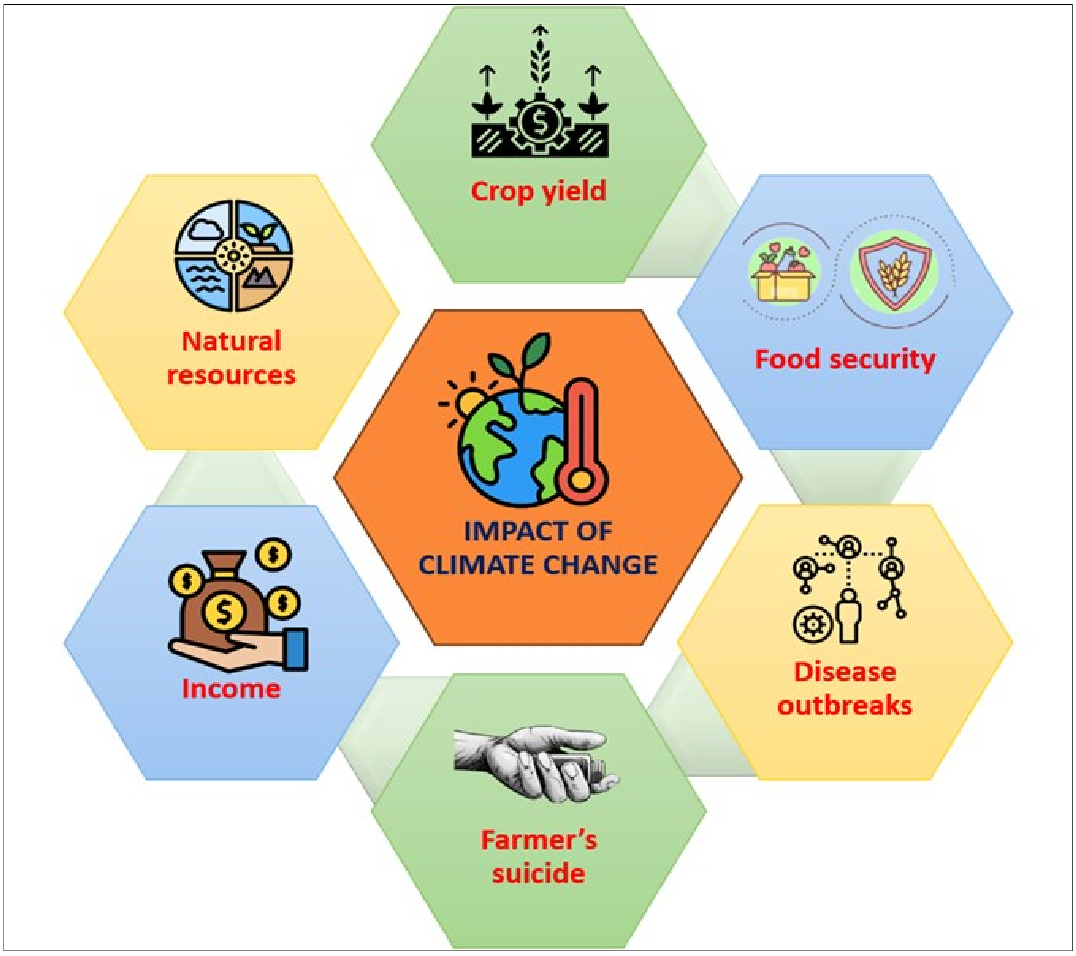

Fig. 1. Key impacts of climate change on agricultural productivity and farmer vulnerability.

that a rise in temperature damaging crops has led to an increase in suicide rate among small farmers in India (21). Climate variability and extreme weather events pose challenges to both crops and animals, their habitats and survival. Climate change may outpace the genetic adaptation of animal species (22). Livestock is a key component of agriculture and contributes to almost 40 % of agricultural GDP. By 2050, there will be a twofold increase in global demand for animal products, mainly driven by improving living standards (23). Changes in precipitation, like more frequent droughts and intense rainfall, can impact forage quality and availability for livestock. Droughts can reduce forage production and limit feed supply, resulting in stunted growth and weight gain among livestock (24). Moreover, a rise in global temperature changes the frequency and severity of heat waves, a big challenge to livestock health and productivity. Heat stress can result in decreased appetite, slower growth, heightened vulnerability to diseases and reduced fertility among livestock. Fish production is projected to decrease by 6 % in global oceans by the year 2100, with a steeper decline of 11 % expected in tropical zones (25). Additionally, an 85 % reduction in both marine and terrestrial production is forecasted, especially in coastal nations under examination.

Climate Change Adaptation Strategies

The big three of climate change are temperature, carbon dioxide and rainfall variability (26). Adaptation is the best way to deal with climate variability and change, as it can reduce the negative impacts of climate change and ensure production (27). Human systems need deliberate "adaptation", which means anticipating climate risks in the future and planning for infrastructure and ecosystem resource management. This preparation is to enable communities to be ready for climate-related challenges in the future (28). The main objective of adaptation is to increase societal resilience to climate change (29). Key adaptation practices are reducing farm areas, changing cropping patterns, growing drought -tolerant varieties, drilling or deepening wells, improving water transfer systems, reducing livestock numbers, modifying feed ingredients and supplementary feeding (30, 31). Most of the research on climate change and adaptation is on assessing vulnerability through qualitative and quantitative methods (32, 33). Access to sustainable irrigation systems is key to increasing food production (34). The farmers used micro irrigation techniques as adaptive measures to deal with the occurrence of prolonged drought, as well as employed a wide range of management strategies to cope with climatic unpredictability through selecting resistant varieties, altering the variety in use and adapting drought-tolerant or resistant types (35). Blend of traditional and improved practices like intercropping, crop rotation and use of drought-tolerant resistant varieties and by delivering essential irrigation during prolonged dry times, usually by giving their crops one or two irrigation cycles (36).

Traditional agriculture includes agroforestry, crop rotation, intercropping, organic composting, cover cropping and integrated crop-livestock systems. These old practices are the foundation of CSA as they are more sustainable and play a big role in mitigating climate change (37). Farmers in dryland areas have implemented various adaptation measures such as growing climate resilient crops, adjusting agricultural calendar, changing crop practices and reducing livestock population (38). Rural households experiencing water stress implemented various agronomic practices to mitigate water scarcity risks (39). Managing water resources by increasing water storage, implementing fair water supply and distribution, keeping rivers healthy and overseeing watershed management can mitigate climate change impacts on water (40). Similarly, developing climate-resilient crops, optimising water use in irrigation, adopting CSA and using indigenous knowledge can increase agricultural production and food security. Technical interventions can equip farmers with scientific analysis of climate parameters for sustainable agriculture management. Rural households experiencing water stress implemented various agronomic practices to mitigate water scarcity risks. The others are reducing area, shortening furrow length, no second crop and increasing fertiliser use (41). Producers have used several absorptive strategies to mitigate the impacts of climate variability or change. These include reducing stock numbers, changing feed ingredients, decreasing feeding frequency and post-harvest grazing. Incorporating local producer experiences and indigenous knowledge into regional and national adaptation policies will strengthen adaptation efforts and reduce vulnerability to climate change (42). The other adaptation measures observed in different regions are summarised in Table 1.

Resilience Mechanisms

Achieving climate resilience and enhancing sustainable rural livelihoods necessitates the improvement of farming systems and the strengthening of the non-farm economy (71). Agricultural communities that exhibit resilience typically demonstrate certain traits, including a strong commitment to sustaining agricultural activities, a reduced inclination to migrate from their villages, minimal job turnover, efforts to enhance and maintain agricultural productivity, growing confidence and positivity regarding the future of agriculture and a proactive approach to adopting climate-resilient strategies in agricultural practices (72). Research has demonstrated that resilience to climate change is influenced by factors such as household income, livelihood diversity, property ownership, social cohesion, place attachment, environmental beliefs, access to water resources and the use of various adaptation measures(73, 74). The concept of CSA has emerged as one of the most widely adopted practices globally, continuing to be implemented universally to promote sustainable agricultural practices and to reduce the negative impacts of climate change (75, 76). CSA offers adaptable, community-centred solutions to address climate fluctuations in agricultural settings, offering a comprehensive approach that safeguards food security (77). Nearly half of the studies highlighted that extension services and awareness outreach play crucial roles in the successful adoption of climate-resilient crops in low- and middle-income countries (78). Human capital enhances the understanding of climate change risks and the necessity of adopting suitable management strategies; Social capital aids in managing contingencies, while natural capital supports productive enterprises; Physical capital helps implement livelihood strategies that boost resilience and financial capital enables the development of adaptation measures and speeds up recovery after shocks (79).

Role of Extension Services and Policy Measures

Extreme droughts and floods, which are linked to climate change, will cause local hardship but often don't get the attention of the international community. So, it's becoming more important to strengthen the ability of smallholder farmers

Table 1. Climate change impacts and adaptation strategies across various regions of the world

Source	Study area	Climate change	Impact on agriculture	Adaptive strategies
(43)	Sri Lanka	Between (1901-2000): Increase in temperature by 0.5°C By 2050s: Expect rainfall to drop 9-17%	Increase in evapotranspiration, Disturbance in the cropping pattern, Soil moisture and yield loss; Crop failure	Transition of planting time, implementation of micro irrigation and reduction of irrigation depth; crop diversification
(44)	South Africa and Ethiopia	Projections: warming is expected to be greater than the global average; temperature increases mostly in the summer; precipitation decreases	Food and water security are under significant danger.	Diversifying crops and varieties, planting shade trees, adopting soil conservation practices, adjusting planting schedules, improving irrigation, altering the area under cultivation and providing supplementary feed for livestock
(45)	Ghana	By 2050, temperatures are expected to rise by about 1.3 to 1.6°C. Rainfall will become more unpredictable, with heavier downpours but fewer rainy days overall.	Long drought periods during the reproductive (particularly grain filling) stage of crops affect grain size, weight and hence yield.	Diversification of crops; alteration of crop planting schedules
(46)	Europe	Increase in warmer temperatures and more frequent extreme weather events	Yield losses, reduced spring crops from drought and shorter growth and declining soil organic carbon.	Crop rotations; crop residue management; re-initialisation
(47)	Finland	Wetter and warmer winters, drier and warmer summers and a higher frequency of extreme events	Longer growing seasons with less snow, more rainfall and greater weather extremes like strong winds, heavy rains and heatwaves.	Intercropping involves combining forage crops (grasses and legumes), under-sowing cereals with perennial grasses and using diverse forage mixtures to enhance soil quality and fertility.
(48)	Brazil	Rising extreme temperatures, reduced average rainfall and more frequent, intense and severe weather events.	Increased heat stress, water scarcity and flood-related damage to crops and rural infrastructure	Adoption of drought- and climate-resilient landraces
(49)	Bangladesh	Projected rise in heat levels	Concern over crop selection in rainfed rice systems.	Shift from traditional rainfed Aman rice to irrigation-based Boro, Aus and other climate-resilient crops, adopting alternative practices like integrated farming and floating gardens.
(50)	Iran, Fars Province	Experiencing extreme droughts	Decline in agricultural water quality and availability, including increased salinity and bitterness.	Environmental stress management, access to education and advisory services and government-led interventions like infrastructure development, organisational support and information dissemination.
(51)	Europe	Between 1990 and 2003, temperatures rose, leading to water shortages, more heatwaves and frequent droughts.	Decreased crop yields and reduced cultivable area, with overall lower productivity in warmer regions	Adaptation is driven by shifts in crop rotations, improved irrigation management, intensive fertiliser use and increased exposure to extreme conditions.
(52)	Scotland	By 2030, 2050 and 2100, projections indicate warmer, wetter winters; hotter, drier summers; and more frequent extreme weather events.	Hotter, drier summers hinder current crop growth but may allow new crop types; flooding and storms cause damage, while warmer, wetter conditions boost grass growth for livestock in western and northern areas; however, extreme heat poses challenges for both crops and animals.	Adaptation strategies include rescheduling planting and harvesting, using climate-resilient crops, improving pasture and soil management, promoting knowledge sharing, offering advisory support, establishing early warning systems and strengthening farmer cooperatives. They also involve optimising fertiliser use, enhancing soil practices for variable moisture conditions, adopting agroforestry for carbon storage, soil stabilisation and livestock shelter, creating diverse income opportunities, conserving biodiversity through habitat development and improving transport and irrigation infrastructure.
(53)	Pakistan	Rising temperatures, extended summers with shorter winters, irregular rainfall, frequent floods, severe droughts, extreme heat waves, glacier melt, rising sea levels and unpredictable weather events such as storms and heavy rains	Significant agricultural losses lead to notable variations in expected crop yields.	Adaptation measures include altering crop types, varieties and planting schedules; planting Eucalyptus along riverbanks to prevent flood-induced soil erosion; improving fertiliser use, seed quality and shade tree selection.

(54)	France	Ongoing climate change is altering seasonal patterns (temperature, frost, wind) and increasing the frequency of extreme events such as droughts and heat waves.	Negative effects include: (i) vegetable losses due to pest pressure, metabolic issues and reduced yield and quality; (ii) farm management challenges from increased labour and complex planning; and (iii) reduced profitability from higher costs and losses. Positive effects include extended growing seasons and opportunities for tunnel crop cultivation.	Adaptation practices include using cover crops, mulching, agroforestry and crop diversification; modifying crop plans; and employing climate-control equipment in tunnels along with efficient irrigation systems.
(55)	Russia	Variations in annual and seasonal temperature and humidity are shifting bioclimatic zone boundaries northward.	Soil degradation, increased erosion and reduced farmand fertility.	Expanding drought-resistant crop cultivation, reclaiming degraded land, adopting minimal or zero tillage to prevent erosion, improving moisture conservation and increasing the use of fertilisers and plant protection measures.
(56)	Italy	Current issues include droughts, strong winds, hail, floods, late frosts, extreme temperatures, heavy rainfall, land unsuitability, saltwater intrusion, erosion and pest or disease damage.	Climate events cause annual crop losses of 10–40% in Italy, with extreme events from 2009–2018 costing the agricultural sector about €14 billion in damages to infrastructure and production.	Eight focus areas: soil management, soil amendments and fertilisers, agronomic practices, crop protection, water management, engineering and digitisation with training, innovative breeding and animal welfare and winemaking technologies.
(57)	Greece	Current conditions: reduced rainfall and higher temperatures.	Water scarcity and higher evapotranspiration cause drought stress, crop damage and elevated wildfire risk.	Regulated irrigation, pruning, grafting, de-leafing and fertilisation management.
(58)	Cyprus	2031–2060: projections indicate steady and significant warming, extended drought periods and decreased annual rainfall.	Yield reductions of up to 9%, a 14–18% rise in early winter sowing, a 20–30% drop in tomato production, nearly stable olive yields and significant losses (24–38%) in late-ripening grape varieties.	Green manure for vegetables, applying regulated deficit irrigation in olive groves, adopting zero tillage and early sowing for wheat and barley, using organic mulch in olive fields, providing artificial shading in vineyards, implementing integrated pest management, intercropping with legumes and developing drought- and heat-tolerant crop varieties.
(59)	China	Current conditions: rising temperatures and declining rainfall	Over the next 20–80 years, rainfed rice, wheat and maize yields are projected to decline by 20–36%, while cotton yields are expected to rise.	National level: Emphasis on small-scale irrigation and drainage systems, building water storage facilities, improving water-use efficiency and promoting research on crop varieties resistant to drought, waterlogging, heat, pests and diseases. Local (farm) level: Adoption of adaptive, high-yield, multi-functional crops and water-saving practices such as plastic mulching, drought-tolerant varieties, stubble retention, minimal tillage and surface plastic irrigation systems.
(60)	Indonesia	Current conditions: altered rainfall patterns, particularly shifts in the timing and length of the dry season	Decline in crop yield and quality, with indirect impacts such as rising pest and disease incidence	Expanding arable land via social forestry, increasing pesticide and inorganic fertiliser use, or promoting organic farming and shifting toward perennial crop cultivation.
(61)	Nepal	Rising temperatures, delayed monsoons, reduced surface and groundwater availability, prolonged droughts and intense but infrequent rainfall leading to floods and landslides.	Impacts include reduced rice area, grain quality and yield; higher evapotranspiration increasing irrigation demand; greater pest and disease infestations, including new species; poor germination and water stress leading to fewer tillers and delayed panicle formation; delayed transplanting due to water shortages; crop losses from heavy rain or hail; damage to water resources and irrigation canals; and soil erosion with declining soil quality.	Cultivating short-duration, pest- and drought-resistant varieties; relocating planting sites; improving irrigation efficiency; strengthening weed and pest management; adopting soil conservation and reduced tillage; practicing seed priming; adjusting crop calendars; shifting to direct-seeded rice; increasing seed rates and fertilizer use; applying more farmyard manure; constructing waterways to manage excess rainfall; growing flood-tolerant varieties; and diversifying to non-rice crops.
(62)	India	Projected climate change indicates greater variability in summer monsoon rainfall.	Soil erosion and nutrient loss lead to land degradation	Conservation agriculture: minimal soil disturbance, continuous crop rotation, conservation or no-tillage, residue retention, organic farming, green manuring, integrated crop-livestock systems and biodiversity conservation.
(63)	USA	For 2010–2039, 2040–2069 and 2070–2099, temperature and summer temperature-humidity index are projected to rise, with overall annual rainfall increasing but summer precipitation declining.	Decreasing cropland area while expanding pasture land	Land use shifting from cultivation to grazing, with reduced cropland and expanded pasture areas

(64)	USA	Current condition: warmer and drier growing seasons	Drought severely restricts green roof productivity, lowering herb yield but enhancing essential oil and antioxidant levels.	Enhancing green roof food production through better roofing materials, water-retaining gels, mulching, subsurface irrigation and supplemental watering to improve yield and quality
(65)	Nigeria	Over the past 30 years, average minimum and maximum temperatures have risen by about 0.25°C and 0.15°C, respectively, with highly variable rainfall. Future trends indicate continued temperature increases.	Affects crop and livestock productivity, water balance, input availability and overall agricultural systems	Tree planting, mixed farming and cropping, soil conservation, using diverse crop varieties, adjusting planting dates and irrigation, applying mulching, adopting zero tillage, forming ridges and modifying planting schedules.
(66)	Kenya	Frequent droughts, occasional floods and unpredictable rainfall patterns.	Risks to food and livelihood security.	Climate-smart practices include efficient irrigation, revised cropping calendars, the use of certified seeds, crop rotation and regular soil testing.
(67)	Netherlands	By 2050, global temperature may rise by 2°C with altered air circulation causing drier summers, or by 1°C without changes in circulation patterns.	Moderate climate change may enhance farm economic performance, while extreme events negate these benefits and increase risks.	Integrated crop and farm adaptations include increasing winter wheat cultivation in root crop –dominated systems.
(68)	Russia	By 2030, compared to 1990–2020, sharp temperature fluctuations are expected, with heavy rainfall in central regions, drought and river drying in the south and worsening water shortages in southern areas.	In central regions, longer sunlight duration will enhance yields and enable the cultivation of crops once limited to southern areas.	Decreasing reliance on chemical inputs and synthetic fertilisers while encouraging the adoption of renewable energy across modern agricultural systems
(69)	Nepal	Current conditions: rapid glacier melting, snowpack reduction, extreme weather events and changing water availability	Adverse effects on water availability and agricultural productivity	Promoting flood, landslide and drought-resilient crop varieties; adopting flood-tolerant hybrids like rice and sugarcane in flood-prone areas; constructing bio-dams to reduce flood and deforestation impacts; implementing intercropping and agroforestry; ensuring sustainable irrigation; improving agricultural information services; introducing rainwater harvesting; expanding flood- and drought-resistant crops; supporting alternative livelihoods; and developing reliable early warning systems for risk management.
(70)	India	Current warming trends are accompanied by more frequent strong wind events, extended summer periods and shorter winters.	Adverse effects on agricultural productivity arise from physiological changes in crops and reductions in grain quality, along with disruptions to key production factors such as water availability, soil fertility and pest dynamics.	Passive adjustments in agricultural practices include shifting sowing and harvesting dates, adopting short-duration crop varieties, practising intercropping, modifying crop structure and increasing investments in irrigation and agroforestry.

in vulnerable communities to manage these climate risks. Extension should focus on educating farmers on their adaptation options to improve their resilience and response capacities. Agricultural extension services contribute to educational programs that improve farmers' ability to cope with the impacts of climate change (80). Significance of involving extension staff in ongoing professional development to enhance their training in climate education and to equip them to effectively convey climate change information to farmers who are highly vulnerable to its impacts has been demonstrated effectively in the literature (81). Another vital role of extension in climate change adaptation is to connect farmers with transport agents, markets, input suppliers and other various factors within the rural sector (82). Future suggestions are that the scientists, policymakers and others should align more closely with farmers' and extension workers' insights on weather changes to enhance the formulation and implementation of adaptation policies (83). Building capacity at local, national and regional levels is crucial for developing countries to adapt to the changing climate.

Conclusion

This review underscores the urgent need for inclusive, multi-level action to address climate change impacts on agriculture. Evidence from diverse contexts highlights that community engagement, nature-based solutions, policy support and technological innovation form the foundation of resilience. To translate these insights into impact, adaptation efforts must be holistic and tailored to local conditions, integrating institutional capacity-building with farmer-led innovations. Future research should focus on evaluating the scalability and cost-effectiveness of these strategies to ensure climate-resilient food systems.

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Authors' contributions

KSP conceptualised the study, conducted the primary literature review, synthesised the findings and drafted the original manuscript. PR supervised the study, provided guidance in framing the article and critically reviewed the manuscript for intellectual content. AM contributed to idea development, reviewed the manuscript and assisted in securing research grants. DGA helped in summarising and revising the manuscript. KR contributed to summarising the manuscript. GSR provided technical inputs. PI contributed to refining the manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

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