Review

Role of agricultural extension in promoting climate-resilient and sustainable farming systems: a review

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© Society for Advancement of Human and Nature (SADHNA) ***Received: 02.06.2026/Accepted: 19.07.2026***

ABSTRACT

Climate change poses an immediate and escalating threat to global agriculture, disproportionately impacting smallholder livelihoods and food security through irregular weather patterns and land degradation. Transitioning toward climate-resilient and sustainable farming systems is critical, yet the success of this transition rests on the effective transfer and co-creation of knowledge. This paper presents a systematic mini-review of literature published between 2000 and 2025, tracking the evolving role of agricultural extension services from traditional, top-down technology transfer models to participatory, pluralistic and digitally enabled innovation networks. The synthesis reveals that agricultural extension has become an indispensable institutional mechanism for translating complex climate science into context-specific practices, such as conservation agriculture, integrated farming and agroforestry. Furthermore, the integration of digital information communication technologies (ICTs) has dramatically scaled up the delivery of real-time weather alerts and adaptive agronomic advice. However, persistent institutional constraints, limited climate literacy among field personnel and systemic inequities in service delivery, particularly concerning women, smallholders and marginalized communities, continue to hinder widespread adoption. The review concludes that future agricultural transformation requires decentralizing extension delivery, adequately blending indigenous wisdom with modern scientific innovations and investing heavily in inclusive, gender-responsive capacity building to ensure no farming community is left behind in the face of a changing climate.

Keywords: Agricultural extension; Climate resilience; Sustainable farming systems; Digital advisories; Participatory learning; Climate-smart agriculture

INTRODUCTION

Agriculture is among the sectors most vulnerable to climate change. Rising temperatures, irregular rainfall, extreme weather events and land degradation pressure global production systems (Anang 2022, Omotayo et al 2025). These challenges increase production risks, threaten food security and affect smallholder livelihoods, particularly in developing countries (Bhagat et al 2025).

Dependent on soil, water and weather, farming systems often struggle to cope with climate variability (Bhatnagar et al 2024). Consequently, developing climate-resilient and sustainable agricultural systems is a global priority to maintain productivity, conserve resources and secure food and livelihoods (Billah et al 2025).

Climate-resilient farming systems help agriculture withstand, adapt to and recover from climate stresses while maintaining or improving productivity (Chourad et al 2024). Sustainable agriculture complements this by balancing economic viability, environmental protection and social well-being. Practices such as conservation agriculture, integrated farming systems, climate-smart technologies, agroforestry, efficient water management and locally adapted crop varieties strengthen farming resilience and sustainability (Chandra et al 2018). However, widespread adoption depends on farmers' knowledge, technical skills, risk perception and access to reliable, timely information, factors essential for promoting sustainable agricultural transformation (Dinesh et al 2015). Agricultural extension serves as a vital link between scientific research and practical field application (El Chami et al 2020, El Chami and

Moujabber 2024, Ferdousi et al 2024). By delivering technical knowledge, building capacity and encouraging improved practices, extension systems translate research into solutions suited to local conditions (Farooq et al 2023).

With growing climate challenges, agricultural extension has evolved beyond traditional technology transfer to promote farmer learning, community participation and informed decision-making for adaptation (Ghadage et al 2024, Ghosh 2019, Hussain et al 2022). Extension professionals now serve as technical and climate advisors, innovation brokers and change facilitators, helping farmers adapt to rapidly changing conditions (Heena et al 2025, Klerkx et al 2009, Sulaiman et al 2012). Over the past two decades, top-down approaches have given way to participatory, pluralistic systems that encourage farmer involvement, knowledge co-creation and multi-stakeholder collaboration (Kamruzzaman et al 2021).

Approaches such as farmer field schools, participatory technology development, climate advisory services and community-based extension have become increasingly important for strengthening farming community resilience. Rapid advances in digital technologies have expanded extension reach and effectiveness through mobile-based advisories, decision support systems and climate information services that provide timely, location-specific information for better-informed management decisions (Kabato et al 2025, Kumar et al 2022).

Despite these advances, constraints such as inadequate institutional capacity, limited financial resources, uneven service coverage and insufficient personnel training on climate change continue to limit extension effectiveness (Babu et al 2013, Sajesh and Suresh 2016). Consequently, resource-poor smallholder farmers, women and tribal communities often have limited access to extension services, increasing their climate vulnerability. Furthermore, failing to adequately integrate indigenous knowledge with scientific recommendations reduces advisory relevance to local conditions and limits adaptation efforts (Loboguerrero et al 2019, Lipper et al 2014, Lou et al 2024, Ma and Rahut 2024).

The study selection followed a systematic multi-stage screening procedure, beginning with title and abstract screening against predefined inclusion criteria, followed by full-text review to confirm suitability (Thottadi and Singh 2024). Documented using the PRISMA framework outlining identification, screening, eligibility and inclusion stages (Fig 1), a quantitative meta-analysis was not performed as the objective was a narrative literature synthesis. Characteristics and key findings of representative studies on agricultural extension for climate adaptation and climate-smart agriculture are given in Table 1.

Data extraction and synthesis

Relevant information was extracted using a standardized framework covering publication year, study location, methodology, extension approaches, institutional settings, climate-resilient practices and sustainability dimensions. Particular attention was given to identifying common themes, emerging trends and extension strategies across agroecological and socio-economic settings. The extracted information was analyzed using qualitative thematic synthesis. Studies were grouped into major thematic areas: participatory extension approaches, climate advisory services, digital and ICT-enabled extension, institutional and policy frameworks and integration of indigenous knowledge systems. This thematic structure enabled a comparative assessment to identify key knowledge patterns, research gaps and emerging directions regarding agricultural extension's role in climate-resilient and sustainable farming systems.

Climate change impact and the need for extension-led resilience

Climate change affects agricultural systems through interconnected environmental, economic and social pathways. Rising temperatures, changing rainfall patterns, frequent extreme weather events and land degradation reduce crop yield stability and increase production uncertainty in rainfed and irrigated systems. These impacts are particularly severe for smallholder farmers, who rely heavily on climate-sensitive natural resources with limited financial capacity and restricted access to institutional support and extension services (Ackryl et al 2023).

Because climate impacts vary across agroecological regions, cropping systems and socio-economic conditions, adaptation strategies must be tailored to local environments. Agricultural extension plays an important role by translating complex climate information into practical, location-specific recommendations. Effective extension services enhance risk awareness and improve understanding of adaptation measures, encouraging farmers to adopt

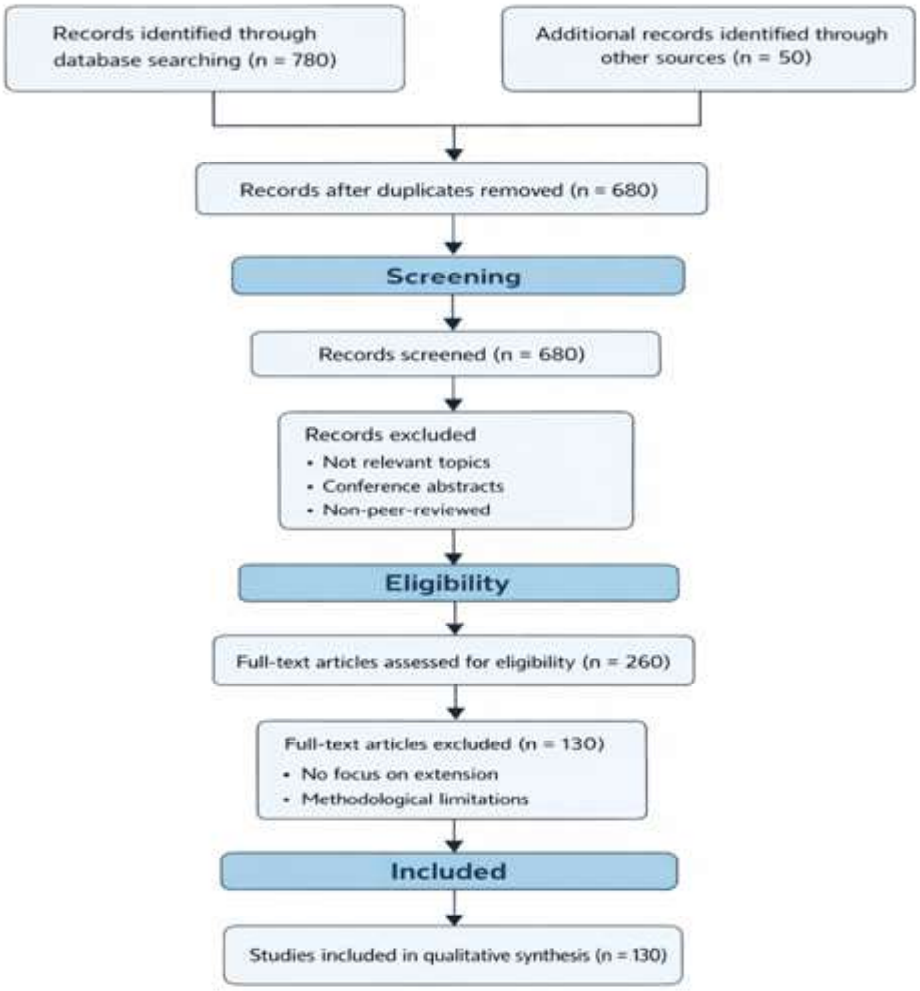

Fig 1. PRISMA flow diagram of the study selection

proactive strategies for climate management (Tunio et al 2024).

Building resilience is a continuous process that depends on learning, adaptation and regular access to reliable information rather than one-time interventions. Agricultural extension supports this process by maintaining regular interaction with farmers, providing timely advisory services and incorporating feedback into extension programmes (Vermeulen et al 2012). Through these ongoing efforts, extension systems help strengthen farmers' capacity to adapt to changing climatic conditions and form a key pillar of climate-resilient and sustainable farming systems.

Evolution of agricultural extension approaches in the climate change context

Agricultural extension has undergone a major transformation over the past two decades. Traditional models focused on top-down technology transfer have evolved into participatory, systems-based and innovation-oriented approaches. Growing climate impacts accelerated this shift by highlighting the limitations of uniform recommendations and reinforcing the need for locally relevant, context-specific solutions (Klerkx et al 2012, Maratha et al 2025). Participatory approaches, including farmer field schools, participatory technology development and community-based learning platforms, are widely recognized as effective strategies for strengthening adaptive capacity. By encouraging active participation, experiential learning and knowledge sharing, these approaches enable farmers to better understand climate risks, test new practices and make informed management decisions (Klerkx et al 2012).

Pluralistic extension systems bringing together public agencies, private organizations, non-governmental organizations and farmer groups are increasingly important. Such collaborative systems combine technical expertise, financial resources and local knowledge, making extension services more

Table 1. Characteristics and key findings of representative studies on agricultural extension approaches for climate change adaptation and climate-smart agriculture

Country/region	Extension approach	Major findings	Reference
Global	Advisory services	Improved climate resilience through sustainable agriculture	El Chami et al (2020)
Australia	Innovation networks	Enhanced adaptation to climate extremes	Kamruzzaman et al (2021)
Ghana	Extension services	Increased adoption of climate-smart technologies	Anang (2022)
China	Digital extension	Improved uptake of adaptation practices	Zheng et al (2024)
Developing countries	Extension support	Strengthened farmers' adaptive capacity	Ferdousi et al (2024)
India	Participatory extension	Improved resilience among farming communities	Chourad et al (2024)
Global	Rural advisory services	Strengthened climate-smart agricultural systems	Billah et al (2025)
India	Capacity building	Improved farmer resilience to climate change	Priya et al (2025)
Global	Advisory systems	Positive linkage between extension and adaptation	Thottadi and Singh (2024)
Global	Knowledge dissemination	Increased adoption of climate-smart agricultural innovations	Khatun et al (2025)

responsive to diverse climate challenges (Sulaiman and Hall 2012). Within these evolving systems, extension professionals increasingly act as facilitators, innovation brokers and coordinators who connect farmers with information, technologies and support networks, rather than serving solely as providers of technical advice (Yiridomoh et al 2025).

Role of extension in promoting climate-resilient farming practices

Agricultural extension plays an important role in promoting climate-resilient farming practices. Through training, technical guidance and continuous support, extension services encourage practices such as crop diversification, mixed cropping, integrated farming systems, agroforestry, conservation tillage, soil moisture conservation and efficient water management (Waqas et al 2025).

These practices enhance resilience by reducing single-crop dependence, improving soil health, boosting biodiversity and stabilizing farm incomes. Extension services also reduce adoption uncertainty through field demonstrations, farmer-to-farmer learning and regular support, increasing confidence in implementing climate-resilient innovations (Ma and Rahut 2024). By integrating sustainability principles into advisory programmes, extension systems help farmers move beyond short-term shock responses toward long-term adaptation, improving productivity while conserving natural resources (Mao et al 2024).

Climate information services and advisory support through extension

The integration of climate information services into agricultural extension has emerged as a significant development. Extension systems increasingly provide weather forecasts, seasonal climate outlooks and early warning information to support timely, climate-responsive farm management (Friedman et al 2022, Hansen et al 2011). Climate information becomes more actionable when combined with practical agronomic advice, enabling farmers to adjust planting dates, select suitable crop varieties, plan irrigation and manage pests effectively. Extension personnel play a vital role by translating complex climate data into location-specific recommendations (Hansen et al 2011, Hansen 2005).

Digital platforms, mobile advisories and decision-support tools have expanded the reach of climate information services, delivering timely information to many farmers. However, effectiveness depends on digital literacy, communication infrastructure and user trust. Consequently, face-to-face interaction and interpersonal communication remain essential for complementing digital advisories and ensuring adoption (Babu et al 2012, Deichmann et al 2016, Sulaiman et al 2012).

Institutional role of extension systems in climate adaptation

Agricultural extension extends well beyond providing technical advice (Klerkx et al 2009, Sulaiman and Hall 2012). Systems facilitate coordination by linking farmers with research institutions, financial organizations, insurance providers and government programmes, improving access to information, technologies and support services essential for climate resilience (Sulaiman and Hall 2012). Because effective adaptation requires multi-sectoral coordination, institutional collaboration is key to successful extension. Strong institutional frameworks enhance programme effectiveness by improving coordination, ensuring service continuity and providing financial and technical support to scale up climate-resilient practices (Davis and Sulaiman 2014, Anon 2012).

Despite these advances, institutional challenges continue to affect performance. Commonly reported constraints include shortages of extension personnel, inadequate funding, limited climate-specific training and fragmented governance structures (Babu et al 2013, Davis and Sulaiman 2014, Nair and Jahagirdar 2022). These limitations reduce extension capacity to reach vulnerable communities and respond effectively to growing climate challenges (Zheng et al 2024).

Equity dimensions in extension-led climate resilience

Women farmers, smallholders, tribal communities and other marginalized groups face significant barriers to extension services due to socio-cultural norms, limited resources and institutional constraints (Zhao et al 2023). Consequently, these groups are less able to benefit from climate-resilient technologies and advisory support. Extension systems are more effective when adopting inclusive, gender-responsive approaches addressing specific community needs (Gumucio et al 2020, Nelson and Forsythe 2023, Priya et al 2026). Community-based extension and integrating indigenous knowledge with scientific recommendations improve advisory relevance, acceptance and effectiveness by aligning with local conditions and cultural practices (Nyong et al 2007, Anon 2012).

Agricultural extension systems must move beyond uniform delivery models to adopt flexible, context-specific approaches. Tailoring strategies to diverse needs, capacities and socio-economic conditions is essential for ensuring equitable knowledge access, strengthening climate resilience and promoting sustainable development (Klerkx et al 2012, Sulaiman and Hall 2012, Anon 2012).

Between 2000 and 2025, agricultural extension played a pivotal role in promoting climate-resilient, sustainable systems by linking research and farming communities (Klerkx et al 2012, Sulaiman and Hall 2012, Anon 2012). During this period, extension evolved from top-down approaches to participatory, farmer-centred, demand-driven models that encourage knowledge sharing, local innovation and continuous learning (Chambers 1994, Klerkx et al 2012, Sulaiman and Hall 2012, Waddington et al 2014). Through climate advisories, capacity building and digital initiatives, professionals helped farmers understand climate risks, adopt resource-efficient technologies and develop resilient livelihoods (Anon 2012, Friedman et al 2022, Gumucio et al 2020, Hansen et al 2011).

Increased use of ICTs, mobile advisories and decision-support tools improved access to timely climate information, enabling better-informed decisions (Aker 2011, Deichmann et al 2016, Fabregas et al 2019, Mittal and Mehar 2012). Simultaneously, extension promoted sustainable practices, such as integrated farming, soil-water conservation, agroecology and climate-smart technologies, that enhance productivity while reducing environmental risks (Altieri et al 2015, Bhati et al 2024). Stronger institutional collaboration, supportive policies and public-private partnerships improved service reach and effectiveness in climate-vulnerable, resource-poor regions (Klerkx et al 2012, Sulaiman and Hall 2012, Anon 2012). Despite these advances, persistent challenges include unequal access, limited institutional capacity and inadequate inclusion of smallholders, women and tribal communities. Addressing these requires strengthening personnel, enhancing institutional capacity, decentralizing delivery and designing locally relevant strategies tailored to diverse socio-ecological conditions (Babu et al 2013, Gumucio et al 2020, Priya et al 2026, Sulaiman and Hall 2012).

CONCLUSION

The literature published between 2000 and 2025 underscores a fundamental truth: scientific breakthroughs in climate-smart agriculture are only as effective as the extension systems delivering them. Over the past quarter-century, agricultural extension evolved from a mechanical conduit for distributing inputs into a dynamic, pluralistic network of climate

advisors, innovation brokers and community facilitators. By championing participatory approaches like farmer field schools and embracing mobile-based digital advisories, extension systems empowered millions of farmers to anticipate climate shocks, optimize resource use and safeguard yields.

However, extension-led climate resilience remains constrained by structural bottlenecks. Financial volatility, under-trained staff and 'one-size-fits-all' recommendations dilute advisory impacts. More critically, the systemic exclusion of women, smallholders and indigenous communities creates a vulnerability gap in regions needing resilience most.

Moving forward, building sustainable farming systems requires shifting institutional priorities away from linear knowledge transfer toward decentralized, collaborative platforms where scientific data and local knowledge complement each other. Investing in climate education for agents, securing long-term funding for extension partnerships and explicitly designing gender-responsive outreach are essential. Ultimately, agricultural extension must be recognized not merely as an administrative link, but as the foundational infrastructure required for a climate-resilient agricultural future.

ACKNOWLEDGEMENTS

The authors express sincere thanks to the Department of Agricultural Extension, Faculty of Agriculture, Annamalai University for the academic support.

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How to cite this article: Kaviya P and Natarajan M 2026. Role of agricultural extension in promoting climate-resilient and sustainable farming systems: a review. Int J Farm Sci 16(4): 19-27; doi: 10.5958/2250-0499.2026.00029.7.