

Supplementary Materials

Agricultural Extension for Resilient Smallholder Farming Systems: Mapping Evidence across Climate, Market, and Livelihood Shocks

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Supplementary Table S1. Database-specific search strategy and supplementary search notes.

Data-base/source	Search field	Boolean search string	Search period	Notes
Scopus	Title, abstract, key-words	TITLE-ABS-KEY ("agricultural extension" OR "rural advisory service*" OR "advisory service*" OR "farmer field school*" OR "farmer training" OR "farmer-to-farmer" OR "climate information service*" OR "weather advisory" OR "digital advisory" OR "digital agriculture" OR "climate-smart agriculture training") AND TITLE-ABS-KEY (smallholder* OR "small-scale farmer*" OR "family farm*" OR "rural household*" OR "small-scale producer*")	1 January 2000-31 May 2026	Used to identify studies linking agricultural extension, smallholder farming, resilience, and climate, market, livelihood, or compound shocks.
Scopus	Title, abstract, key-words	TITLE-ABS-KEY ("climate information service*" OR "weather advisory" OR "seasonal forecast*" OR "early warning" OR "climate service*" OR "digital advisory" OR "mobile advisory") AND TITLE-ABS-KEY (farmer* OR smallholder* OR "rural household*")	1 January 2000-31 May 2026	Used to capture climate information services, weather advisories, early warning, digital advisory tools, and risk-communication studies.
Scopus	Title, abstract, key-words	TITLE-ABS-KEY ("market-oriented extension" OR "value chain extension" OR "financial advisory" OR credit OR insurance OR "market information" OR "livelihood diversification") AND TITLE-ABS-KEY (smallholder* OR farmer*) AND TITLE-ABS-KEY (resilience OR "income stability" OR "food security" OR vulnerability OR "market shock*" OR "livelihood shock*")	1 January 2000-31 May 2026	Used to identify market-oriented, financial, and livelihood advisory studies relevant to resilience.
Web of Science Core Collection	Topic	TS ("agricultural extension" OR "rural advisory service*" OR "advisory service*" OR "farmer field school*" OR "farmer training" OR "farmer-to-farmer" OR "climate information service*" OR "weather advisory" OR "digital advisory" OR "digital agriculture" OR "climate-smart agriculture training") AND TS (smallholder* OR "small-scale farmer*" OR "family farm*" OR "rural household*" OR "small-scale producer*") AND TS (resilience OR "adaptive capacity" OR "absorptive capacity" OR "transformative capacity" OR coping OR adaptation OR "vulnerability reduction" OR "livelihood security") AND TS ("climate shock*" OR drought OR flood OR cyclone OR "rainfall variability" OR "heat stress" OR "market shock*" OR "price volatility" OR "input cost*" OR "livelihood shock*" OR "food insecurity" OR "compound shock*")	1 January 2000-31 May 2026	Parallel search to Scopus for cross-database coverage of extension-resilience literature.
Web of Science Core Collection	Topic	TS ("climate information service*" OR "weather advisory" OR "seasonal forecast*" OR "early warning" OR "climate service*" OR "digital advisory" OR "mobile advisory") AND TS (farmer* OR smallholder* OR "rural household*") AND TS (resilience OR preparedness OR adaptation OR "risk communication" OR "anticipatory decision*")	1 January 2000-31 May 2026	Used to capture climate-service, weather-information, and digital advisory studies.

Data-base/source	Search field	Boolean search string	Search period	Notes
Web of Science Core Collection	Topic	TS ("market-oriented extension" OR "value chain extension" OR "financial advisory" OR credit OR insurance OR "market information" OR "livelihood diversification") AND TS (smallholder* OR farmer*) AND TS (resilience OR "income stability" OR "food security" OR vulnerability OR "market shock*" OR "livelihood shock*")	1 January 2000-31 May 2026	Used to identify market, livelihood, credit, insurance, and value-chain extension studies.
Google Scholar	Keyword search	"agricultural extension" "smallholder resilience"; "climate information services" "smallholder farmers" resilience; "farmer field schools" "climate resilience"; "digital advisory" smallholder resilience; "market-oriented extension" smallholder resilience.	1 January 2000-31 May 2026	Used only for backward/forward citation checking and identification of highly relevant missed records.

Note: Record counts refer to records retrieved before duplicate removal. Google Scholar was used only for supplementary identification through targeted searching and citation tracking. Search date was 1 June, 2026.

Purpose: This table reports the database search strategy used to identify studies on agricultural extension, rural advisory services, resilient smallholder farming systems, and climate, market, livelihood, and compound shocks.

Supplementary Table S2. Data-charting and extraction form.

Extraction domain	Data item	Description/coding instruction
Bibliographic information	Author(s)	Record all authors as reported in the publication.
	Year	Record publication year.
	Title	Record full article title.
	Journal/source	Record journal or publication source.
	DOI	Record DOI where available.
Screening information	Document type	Code as empirical article, conceptual article, systematic review, scoping review, evidence synthesis, mixed-method study, participatory study, or policy-oriented study.
	Database/source	Record whether the study was identified through Scopus, Web of Science Core Collection, Google Scholar, or citation tracking.
	Screening decision	Code as included, excluded at title/abstract stage, or excluded at full-text stage.
	Exclusion reason	Record reason for exclusion where applicable: duplicate, no smallholder focus, no extension/advisory component, technical agronomy only, weak resilience/shock linkage, non-agricultural resilience, insufficient detail, or other.
Study context	Country/region	Record country, region, or global/cross-country scope.
	Farming system	Code as rain-fed, irrigated, mixed crop-livestock, livestock-based, semi-arid, coastal, pastoral, cereal-based, horticultural, or multi-system.
	Study population	Code as smallholder farmers, rural households, women farmers, farmer groups, pastoralists, value-chain actors, or mixed rural sample.
Methodology	Research design	Record quantitative, qualitative, mixed-method, case study, participatory research, review, scoping review, systematic review, conceptual analysis, modelling, or policy analysis.
	Data source	Record survey, interviews, focus groups, participatory data, secondary data, literature corpus, policy documents, remote sensing/spatial data, or mixed sources.
	Analytical method	Record regression, SEM, matching, resilience index, vulnerability assessment, thematic synthesis, evidence synthesis, mapping, case comparison, or other method.
Shock domain	Primary shock type	Code climate, market, livelihood, compound/cascading, or multiple.
	Specific shock	Record drought, flood, rainfall variability, cyclone, heat stress, pest pressure, input-price increase, market disruption, food insecurity, labor shortage, COVID-19, or other.
Extension/advisory system	Extension modality	Code public extension, farmer field school, farmer-to-farmer extension, farmer extension facilitator, climate information service, digital advisory, market-oriented extension, financial advisory, gender-responsive extension, participatory innovation, or livelihood advisory.
	Delivery actor	Record government agency, NGO, farmer organization, cooperative, private actor, climate-service provider, community facilitator, digital platform, value-chain actor, or mixed actor network.
	Advisory content	Record climate-smart agriculture, weather forecast, seed/inputs, soil/water management, crop/livestock diversification, market information, credit/insurance, livelihood diversification, or social protection linkage.
Mechanism	Resilience-building mechanism	Code risk awareness, knowledge translation, adaptive practice change, social learning, peer diffusion, service access, market linkage, institutional brokerage, trust, empowerment, or inclusion.
Resilience capacity	Capacity targeted or observed	Code the overarching capacity as absorptive, adaptive, transformative, or multiple. Where relevant, code farm-level, livelihood, or market adaptation as a subdimension of adaptive capacity and collective action as a cross-cutting mechanism supporting adaptive and/or transformative capacity.
Outcomes	Farm outcome	Record adoption, productivity, yield, crop loss, production risk, input use, or climate-smart practice change.
	Livelihood outcome	Record food security, income stability, livelihood diversification, welfare, coping, reduced vulnerability, or recovery capacity.

Extraction domain	Data item	Description/coding instruction
Equity and context	Resilience metric	Record resilience index, adaptive-capacity score, vulnerability measure, recovery measure, or qualitative resilience finding.
	Equity dimension	Record gender, youth, wealth, landholding, education, digital access, location, marginalization, or other distributional dimension.
	Contextual moderator	Record agroecology, infrastructure, market access, institutional quality, advisory quality, digital connectivity, or trust.
Evidence strength	Main finding	Summarize the main finding relevant to agricultural extension and resilience.
	Limitations	Record reported or inferred limitations such as cross-sectional design, limited causal inference, short follow-up, weak equity disaggregation, or limited transferability.
	Appraisal rating	Record the interpretive relevance and methodological-transparency judgement where applicable.
Synthesis relevance	Relevance to RQ1	Record contribution to shock-domain mapping.
	Relevance to RQ2	Record contribution to extension modalities and delivery systems.
	Relevance to RQ3	Record contribution to mechanisms and resilience capacities.
	Relevance to RQ4	Record contribution to farming and livelihood outcomes.
	Relevance to RQ5	Record contribution to conceptual, methodological, geographical, or equity gaps.

Purpose: This table reports the data-extraction fields used to chart the included studies and support framework-based thematic synthesis.

Supplementary Table S3. Characteristics of the 58 included studies

Serial	Author(s)	Objective	Key findings	Implications
1	Abegunde et al. (2019)	Examine the Dynamics of Climate Change Adaptation in Sub-Saharan Africa: A Review of Climate-Smart Agriculture among Small-Scale Farmers	Climate-smart agriculture and advisory support were reported as supporting smallholder adaptive capacity, but adoption depends on resources, context, and institutional support.	Provides evidence for the climate-adaptation pathway but indicates that extension must be linked with resources and institutions.
2	Abid et al. (2020)	Examine ex-ante and ex-post coping strategies for climatic shocks and adaptation determinants in rural Malawi	Smallholders use both ex-ante and ex-post coping strategies, showing that resilience depends on preparedness as well as post-shock adjustment.	Supports the distinction between absorptive and adaptive resilience capacities.
3	Acevedo et al. (2020)	Examine a scoping review of adoption of climate-resilient crops by small-scale producers in low- and middle-income countries	Adoption of climate-resilient crops is shaped by information, input access, institutions, and local suitability, not only technology availability.	Shows why technology adoption should be interpreted through advisory systems and enabling conditions.
4	Ado et al. (2019)	Examine livelihood strategies and household resilience to food insecurity: insight from a farming community in Aguié district of Niger	Household resilience is shaped by livelihood diversification, food security, assets, and the ability to avoid erosive coping strategies.	Supports the livelihood-resilience pathway beyond farm-level technology adoption.
5	Amadu (2022)	Examine farmer extension facilitators as a pathway for climate smart agriculture: evidence from southern Malawi	Farmer extension facilitators and peer learning can expand advisory reach and improve locally trusted climate-smart practice diffusion.	Supports farmer-to-farmer and community-based extension as resilient infrastructure.
6	Antwi-Agyei et al. (2014)	Examine livelihood adaptations to climate variability: Insights from farming households in Ghana	Smallholder adaptation involves changes in livelihoods as well as farm practices under climate variability.	Shows why extension must consider household livelihood strategies, not only crop practices.
7	Aschinger et al. (2023)	Examine smallholder livelihood resilience to climate variability in South-Eastern Kenya, 2012–2015	Household resilience is shaped by livelihood diversification, food security, assets, and the ability to avoid erosive coping strategies.	Supports the livelihood-resilience pathway beyond farm-level technology adoption.
8	Azzarri et al. (2022)	Examine sex-disaggregated agricultural extension and weather variability in Africa south of the Sahara	Sex-disaggregated analysis shows that extension access and weather variability have uneven effects across men and women farmers.	Supports the need for gender-disaggregated and inclusive extension analysis.
9	Batung et al. (2023)	Examine credit access and perceived climate change resilience of smallholder farmers in semi-arid northern Ghana	Credit access and financial support influence smallholders ability to invest in adaptation and perceive themselves as resilient.	Supports linking extension with credit, finance, and risk-management services.
10	Cavatassi et al. (2025)	Examine enhancing households' livelihoods in agrifood systems: The role of women's empowerment	Women's empowerment is linked to stronger livelihood outcomes and more inclusive agrifood-system resilience.	Supports gender-transformative extension and empowerment-oriented resilience outcomes.

Serial	Author(s)	Objective	Key findings	Implications
11	Cohn et al. (2017)	Examine smallholder Agriculture and Climate Change	Smallholder agriculture is highly exposed to climate change and requires integrated adaptation support across knowledge, policy, and institutions.	Provides conceptual grounding for climate exposure and multidimensional vulnerability.
12	Cooper et al. (2008)	Examine coping better with current climatic variability in the rain-fed farming systems of sub-Saharan Africa: An essential first step in adapting to future climate change?	Near-term coping with climate variability is a necessary foundation for longer-term adaptation in rain-fed systems.	Shows why current climate variability must be addressed through practical advisory systems.
13	Davis et al. (2021)	Examine towards food supply chain resilience to environmental shocks	Food-system resilience depends on reducing vulnerability across supply chains, markets, and environmental shocks.	Supports integration of market and supply-chain risks into extension-resilience research.
14	Descheemaeker et al. (2016)	Examine climate change adaptation and mitigation in smallholder crop–livestock systems in sub-Saharan Africa: a call for integrated impact assessments	Integrated crop-livestock assessments are needed to evaluate adaptation and mitigation options in smallholder systems.	Supports integrated farm-system approaches to resilience measurement and advisory design.
15	Douxchamps et al. (2017)	Examine monitoring and evaluation of climate resilience for agricultural development – A review of currently available tools	Existing tools measure agricultural climate resilience unevenly and require clearer indicators of recovery, adaptation, and transformation.	Supports the need for explicit resilience indicators rather than adoption-only outcomes.
16	Endalew et al. (2020)	Examine effects of climate shocks on Ethiopian rural households: an integrated livelihood vulnerability approach	Integrated vulnerability approaches show how climate shocks affect rural livelihoods through exposure, sensitivity, and adaptive capacity.	Supports mapping climate shocks through livelihood vulnerability and adaptive capacity.
17	Goodwin et al. (2022)	Examine what is the evidence linking financial assistance for drought-affected agriculture and resilience in tropical Asia? A systematic review	Financial assistance can support drought resilience when linked to farmers' capacity to recover and invest in adaptation.	Supports financial and social-protection linkages within extension systems.
18	Haworth et al. (2018)	Examine geographic information and communication technologies for supporting smallholder agriculture and climate resilience	Geographic information and communication technologies can support climate resilience when they are usable and locally relevant.	Supports blended digital and human advisory approaches for climate resilience.
19	Holland et al. (2017)	Examine mapping adaptive capacity and smallholder agriculture: applying expert knowledge at the landscape scale	Adaptive capacity can be mapped spatially, showing that household and landscape contexts shape resilience options.	Supports context-sensitive analysis of adaptive capacity across landscapes.
20	Jena et al. (2023)	Examine determinants of adoption of climate resilient practices and their impact on yield and household income	Adoption of climate-resilient practices was associated with improved yield and income when farmers have enabling support.	Supports the practice-change pathway from extension to yield and income outcomes.

Serial	Author(s)	Objective	Key findings	Implications
21	Kalidou et al. (2024)	Examine the value of indigenous knowledge for enhancing smallholders' resilience to climate change and food insecurity: a case study of small-scale irrigation system in Niger	Indigenous and local knowledge was reported as supporting context-specific adaptation and food-security resilience.	Supports participatory and locally grounded advisory systems.
22	Kansiime et al. (2016)	Examine enhancing resilience of farmer seed system to climate-induced stresses: Insights from a case study in West Nile region, Uganda	Seed-system resilience depends on farmer access to diverse, locally adapted, and climate-resilient seed options.	Supports input and seed-system linkages as part of resilience-enabling extension.
23	Khatibu et al. (2025)	Examine effectiveness of climate information services in Sub-Saharan Africa's agricultural sector: a systematic review of what works, what doesn't work, and why	Climate information services was associated with improved farm decision-making when forecasts are timely, understandable, and actionable.	Supports climate information as a risk-communication and anticipatory-decision mechanism.
24	Koczberski et al. (2018)	Examine diffusing Risk and Building Resilience through Innovation: Reciprocal Exchange Relationships, Livelihood Vulnerability and Food Security amongst Smallholder Farmers in Papua New Guinea	Reciprocal exchange and social relations can diffuse risk and support food security under livelihood stress.	Supports social learning and informal support as part of resilient infrastructure.
25	Kuhl (2018)	Examine potential contributions of market-systems development initiatives for building climate resilience	Market-systems development can contribute to climate resilience when it improves incentives, finance, and value-chain coordination.	Supports market-aware extension and value-chain linkage for resilience.
26	Lidder et al. (2025)	Examine innovation and technology for achieving resilient and inclusive rural transformation	Innovation and technology can support resilient rural transformation when inclusion and institutional capacity are addressed.	Supports long-term transformative capacity and inclusive innovation systems.
27	Lipper et al. (2022)	Examine how does climate change affect the evidence we need for agricultural development?	Climate change reshapes the type of evidence needed for agricultural development and resilience-oriented policy.	Supports a more rigorous evidence agenda for agricultural development under climate uncertainty.
28	Lutta et al. (2024)	Examine building climate-resilient value chains in arid and semi-arid regions: a VC-ARID approach for rangeland adaptation in Kenya	Climate-resilient value chains require advisory, market, and coordination support across producers and downstream actors.	Supports climate-market integration in advisory systems.
29	Makate et al. (2019)	Examine increasing resilience of smallholder farmers to climate change through multiple adoption of proven climate-smart agriculture innovations. Lessons from Southern Africa	Multiple adoption of CSA practices may increase resilience, but farmers face resource and information constraints.	Supports the need to assess combinations of practices rather than single adoption outcomes.

Serial	Author(s)	Objective	Key findings	Implications
30	Mapfumo et al. (2016)	Examine building on indigenous knowledge to strengthen the capacity of smallholder farming communities to adapt to climate change and variability in southern Africa	Indigenous and local knowledge was reported as supporting context-specific adaptation and food-security resilience.	Supports participatory and locally grounded advisory systems.
31	Marsden et al. (2023)	Examine smallholder Farming during COVID-19: A Systematic Review Concerning Impacts, Adaptations, Barriers, Policy, and Planning for Future Pandemics	Pandemic-related disruptions exposed smallholder vulnerability to compound livelihood and market shocks.	Supports inclusion of livelihood, market, and compound shocks in the review framework.
32	McCord et al. (2015)	Examine crop diversification as a smallholder livelihood strategy within semi-arid agricultural systems near Mount Kenya	Crop diversification is an important livelihood strategy for spreading risk in semi-arid smallholder systems.	Supports livelihood and farm diversification as adaptive resilience mechanisms.
33	Mekonnen et al. (2024)	Examine building resilience in Sub-Saharan Africa's food systems: Diversification, traceability, capacity building and technology for overcoming challenges	Food-system resilience requires diversification, traceability, capacity building, and partnerships.	Supports cross-sector coordination and partnerships as resilience-building mechanisms.
34	Michalscheck et al. (2023)	Examine preparing for, coping with and bouncing back after shocks. A nuanced resilience assessment for smallholder farms and farmers in Northern Ghana	Resilience assessment should distinguish preparedness, coping, and recovery rather than treating resilience as a single outcome.	Supports mechanism-based and multidimensional resilience measurement.
35	Mohammed et al. (2021)	Examine livelihood diversification strategies and resilience to climate change in semi-arid northern Ghana	Livelihood diversification contributes to climate resilience by reducing dependence on a single farm income source.	Supports livelihood adaptive capacity as a major extension outcome.
36	Murray et al. (2016)	Examine smallholder Farmers and Climate Smart Agriculture: Technology and Labor-productivity Constraints amongst Women Smallholders in Malawi	Women smallholders face technology, labor, and productivity constraints that limit CSA adoption and resilience.	Supports analysis of gendered barriers to CSA and extension benefits.
37	Ngigi et al. (2021)	Examine livestock Diversification for Improved Resilience and Welfare Outcomes Under Climate Risks in Kenya	Livestock diversification was associated with improved resilience and welfare under climate-risk conditions.	Supports diversification as a pathway to welfare and resilience.
38	Njuguna et al. (2025)	Examine silicon Savannah and smallholder farming: How can digitalization contribute to sustainable agricultural transformation in Africa?	Digitalization can support agricultural transformation but can also reproduce exclusion without complementary institutions and human facilitation.	Supports digital extension but warns against technology-only solutions.
39	Nkiaka et al. (2019)	Examine identifying user needs for weather and climate services to enhance resilience to climate shocks in sub-Saharan Africa	Weather and climate services are useful only when designed around user needs and decision contexts.	Supports user-centered design of last-mile climate services.
40	Ofosu-Ampong et al. (2025)	Examine digital agro-advisory tools in the global south: a behavioural analysis of impacts, and future directions	Digital agro-advisory tools can affect farmer behavior but require attention to trust, usability, literacy, and local context.	Supports attention to digital inclusion, behavior, and trust.

Serial	Author(s)	Objective	Key findings	Implications
41	Panja et al. (2026)	Examine mapping resilience pathway of smallholder farming community to cyclone-led climate disasters in coastal West Bengal, India	Cyclone-prone smallholders follow differentiated resilience pathways shaped by exposure, assets, institutions, and livelihood options.	Supports compound-shock and pathway-based resilience analysis.
42	Petersen-Rockney et al. (2021)	Examine narrow and Brittle or Broad and Nimble? Comparing Adaptive Capacity in Simplifying and Diversifying Farming Systems	Diversified farming systems may be broader and more adaptive than simplified systems under stress.	Supports comparing diversified and simplified systems in resilience research.
43	Pienaaah et al. (2024)	Examine farmer field schools, climate action plans and climate change resilience among smallholder farmers in Northern Ghana	Farmer field schools and climate action plans was reported as supporting learning, planning, and collective resilience.	Supports participatory learning and collective action as extension mechanisms.
44	Porciello et al. (2022)	Examine digital agriculture services in low- and middle-income countries: A systematic scoping review	Digital agriculture services in LMICs remain heterogeneous and require stronger evidence on inclusion and outcomes.	Supports systematic mapping of digital advisory tools and evidence gaps.
45	Ramilan et al. (2022)	Examine quantifying Farm Household Resilience and the Implications of Livelihood Heterogeneity in the Semi-Arid Tropics of India	Household resilience varies by livelihood heterogeneity, assets, and exposure to semi-arid risk.	Supports measurement of household resilience under heterogeneous livelihood conditions.
46	Saran et al. (2024)	Examine interventions promoting resilience through climate smart agricultural practices for women farmers: A systematic review	Women-focused CSA interventions can promote resilience but require attention to gendered constraints and empowerment.	Supports gender-responsive and gender-transformative extension policy.
47	Silici et al. (2021)	Examine building adaptive capacity of smallholder agriculture to climate change: evidence synthesis on learning outcomes	Learning interventions can build adaptive capacity when they improve knowledge, experimentation, and practice change.	Supports learning outcomes as intermediate mechanisms in resilience-building.
48	Singh et al. (2025)	Examine mapping the climate and agronomic digital advisory services landscape in West and Central Africa: A step towards making food systems productive and climate resilient	Digital climate and agronomic advisory services are expanding but require localization and last-mile delivery capacity.	Supports last-mile digital advisory design for resilience.
49	Staub et al. (2021)	Examine farmer-led participatory extension leads Haitian farmers to anticipate climate-related risks and adjust livelihood strategies	Farmer-led participatory extension can help farmers anticipate climate risks and adjust livelihood strategies.	Supports participatory extension as a direct mechanism for anticipatory action.
50	Tambo et al. (2017)	Examine enhancing resilience to climate shocks through farmer innovation: evidence from northern Ghana	Farmer innovation was identified as contributing to resilience by enabling locally adapted responses to climate shocks.	Supports recognizing farmers as innovators rather than passive technology recipients.
51	Tamru et al. (2025)	Examine climate information services enhance farmers' resilience to climate change: Impacts on agricultural productivity	Climate information services was associated with improved productivity and resilience when farmers use them in farm decisions.	Supports assessing whether climate information changes productivity and decisions.

Serial	Author(s)	Objective	Key findings	Implications
52	Thottadi et al. (2024)	Examine climate-smart agriculture (CSA) adaptation, adaptation determinants and extension services synergies: a systematic review	Extension services are central to CSA adaptation, but impacts depend on institutional and farmer-level determinants.	Supports integrating extension services into CSA adaptation research.
53	Tripathi et al. (2021)	Examine impacts of COVID-19 on Diverse Farm Systems in Tanzania and South Africa	COVID-19 disrupted diverse farm systems and highlighted the importance of adaptive planning and institutional support.	Supports analyzing non-climatic shocks and compound disruptions.
54	Vernooy (2022)	Examine does crop diversification lead to climate-related resilience? Improving the theory through insights on practice	Crop diversification can support climate-related resilience, but pathways depend on practice, scale, and livelihood context.	Supports stronger theorization of diversification-resilience pathways.
55	Warner et al. (2022)	Examine factors that influence the use of climate information services for agriculture: A systematic review	Use of climate information services depends on relevance, trust, access, timing, and institutional design.	Supports identifying barriers to use of climate information services.
56	Wekesa et al. (2018)	Examine effect of climate-smart agricultural practices on household food security in smallholder production systems: Micro-level evidence from Kenya	Climate-smart practices was associated with improved household food security when extension and resource access support adoption.	Supports food security as a stronger outcome than adoption alone.
57	Williams et al. (2018)	Examine a systematic review of how vulnerability of smallholder agricultural systems to changing climate is assessed in Africa	Vulnerability assessments often vary in indicators and methods, limiting comparability across smallholder systems.	Supports methodological transparency in vulnerability and resilience assessment.
58	Williams et al. (2020)	Examine resilience and equity: Quantifying the distributional effects of resilience-enhancing strategies in a smallholder agricultural system	Resilience-enhancing strategies have distributional effects and must be assessed for equity as well as average benefits.	Supports equity-sensitive evaluation of resilience strategies.

Purpose: This table summarizes the 58 studies retained for qualitative synthesis, including author(s), objective, study design, key findings, and relevance to the review framework.

Supplementary Table S4. Thematic coding framework for agricultural extension and smallholder resilience.

Theme	Relevant subtheme	Description	Sources
Extension interventions and delivery systems	Public and community extension	Government advisory services, local extension agents, community facilitators, and public-sector support.	(Amadu, 2022; Pienaaah & Luginaah, 2024; Silici et al., 2021; Staub & Clarkson, 2021)
	Farmer field schools and participatory learning	Experiential learning, demonstration, experimentation, and collective problem-solving.	(Kalidou et al., 2024; Pienaaah & Luginaah, 2024; Silici et al., 2021; Tambo & Wünscher, 2017)
	Farmer-to-farmer extension	Peer learning, lead farmers, farmer extension facilitators, and horizontal knowledge diffusion.	(Amadu, 2022; Staub & Clarkson, 2021; Tambo & Wünscher, 2017)
	Climate information and weather advisory services	Seasonal forecasts, early warnings, weather advisories, and climate-risk communication.	(Khatibu & Ngowi, 2025; Nkiaka et al., 2019; Tamru et al., 2025; Warner et al., 2022)
	Digital agro-advisory tools	Mobile platforms, ICT-based advisory services, data-enabled recommendations, and digital extension.	(Haworth et al., 2018; Njuguna et al., 2025; Ofosu et al., 2025; Porciello et al., 2022; Singh et al., 2025)
	Climate-smart agriculture training	Extension supports for improved seeds, soil management, water management, conservation agriculture, and sustainable intensification.	(Abegunde et al., 2019; Descheemaeker et al., 2016; Makate et al., 2019; Thottadi & Singh, 2024; Wekesa et al., 2018)
Resilience-building mechanisms	Market, financial, and livelihood advisory services	Value-chain support, price information, credit, insurance, savings, and livelihood diversification advice.	(Batung et al., 2023; Goodwin et al., 2022; Kuhl, 2018; Lutta et al., 2024; Singh et al., 2025)
	Gender-responsive and inclusive extension	Advisory approaches designed to reach women, youth, poorer farmers, and socially marginalized groups.	(Azzarri & Nico, 2022; Cavatassi et al., 2025; Murray et al., 2016; Saran et al., 2024)
	Risk awareness and anticipation	Extension improves understanding of climate, market, and livelihood risks and supports earlier decisions.	(Cooper et al., 2008; Khatibu & Ngowi, 2025; Nkiaka et al., 2019; Staub & Clarkson, 2021; Warner et al., 2022)
	Knowledge translation	Advisory services convert scientific, technical, climate, and market information into practical farm decisions.	(Kalidou et al., 2024; Lipper et al., 2022; Mapfumo et al., 2016; Silici et al., 2021)
	Adaptive practice change	Farmers adjust crops, water use, soil management, livestock systems, and livelihood strategies.	(Antwi & Antwi-Agyei, 2023; Jena et al., 2023; Makate et al., 2019; Vernooy, 2022; Wekesa et al., 2018)
	Social learning and peer diffusion	Farmers learn through groups, demonstrations, farmer networks, and local experimentation.	(Amadu, 2022; Koczberski et al., 2018; Pienaaah & Luginaah, 2024; Staub & Clarkson, 2021; Tambo & Wünscher, 2017)
	Access to inputs, finance, and services	Extension links farmers to seeds, fertilizer, irrigation, credit, insurance, social protection, and public services.	(Acevedo et al., 2020; Batung et al., 2023; Goodwin et al., 2022; Kansime & Mastenbroek, 2016; Wekesa et al., 2018)
	Market linkage and bargaining capacity	Extension improves access to buyers, price information, value chains, postharvest systems, and market negotiation.	(Davis et al., 2021; Kuhl, 2018; Lutta et al., 2024; Mekonnen et al., 2024; Singh et al., 2025)

Theme	Relevant subtheme	Description	Sources
Resilience capacities	Institutional brokerage and trust	Extension connects farmers with institutions, climate-service providers, farmer organizations, and support systems.	(Azzarri & Nico, 2022; Cavatassi et al., 2025; Lidder et al., 2025; Saran et al., 2024; Warner et al., 2022)
	Empowerment and inclusion	Extension strengthens agency, confidence, participation, collective voice, and decision-making capacity.	(Azzarri & Nico, 2022; Cavatassi et al., 2025; Lidder et al., 2025; Saran et al., 2024; T. G. Williams et al., 2020)
	Absorptive capacity	Ability to cope with and withstand shocks through preparedness, early warning, savings, and short-term risk management.	(Abid et al., 2020; Cooper et al., 2008; Michalscheck et al., 2023; Tamru et al., 2025)
	Farm-level adaptive capacity	Ability to adjust production through crop diversification, improved seeds, soil management, water management, and climate-smart practices.	(Acevedo et al., 2020; Descheemaeker et al., 2016; Jena et al., 2023; Petersen-Rockney et al., 2021; Vernoooy, 2022)
	Livelihood adaptive capacity	Ability to stabilize income and reduce risk through livelihood diversification, mixed farming, and nonfarm activities.	(Ado et al., 2019; Antwi & Antwi-Agyei, 2023; McCord et al., 2015; Mohammed et al., 2021; Ngigi et al., 2021)
	Market adaptive capacity	Ability to respond to price, demand, and input-market changes through market information and value-chain participation.	(Davis et al., 2021; Kuhl, 2018; Lutta et al., 2024; Singh et al., 2025)
	Collective resilience capacity	Capacity built through farmer organizations, cooperatives, group learning, collective action, and local innovation.	(Kalidou et al., 2024; Koczberski et al., 2018; Pienaaah & Luginaah, 2024; Staub & Clarkson, 2021; Tambo & Wünscher, 2017)
Farming and livelihood outcomes	Transformative capacity	Ability to change structural conditions through institutional reform, gender empowerment, inclusive markets, and long-term innovation systems.	(Lidder et al., 2025; Mekonnen et al., 2024; Njuguna et al., 2025; T. G. Williams et al., 2020)
	Adoption of adaptive practices	Adoption of climate-smart, agroecological, conservation, digital, or risk-reducing practices.	(Acevedo et al., 2020; Jena et al., 2023; Makate et al., 2019; Tamru et al., 2025; Thottadi & Singh, 2024)
	Production and risk reduction	Reduced crop loss, improved productivity, lower production risk, and more stable farm performance.	(Jena et al., 2023; Tamru et al., 2025; Thottadi & Singh, 2024; Wekesa et al., 2018)
	Food security	Improved food availability, access, utilization, and stability among smallholder households.	(Ado et al., 2019; Kalidou et al., 2024; Koczberski et al., 2018; Mohammed et al., 2021; Wekesa et al., 2018)
	Income and livelihood stability	Improved income security, reduced poverty exposure, and diversified livelihood sources.	(Ado et al., 2019; Batung et al., 2023; Jena et al., 2023; McCord et al., 2015; Ngigi et al., 2021)
	Reduced vulnerability	Lower sensitivity to climate, market, and livelihood shocks and stronger recovery capacity.	(Endalew & Sen, 2020; Ramilan et al., 2022; P. A. Williams et al., 2018; T. G. Williams et al., 2020)
	Resilience measurement outcomes	Use of resilience indices, adaptive-capacity scores, vulnerability measures, or livelihood-resilience indicators.	(Douxchamps et al., 2017; Holland et al., 2017; Michalscheck et al., 2023; Ramilan et al., 2022; P. A. Williams et al., 2018)

Theme	Relevant subtheme	Description	Sources
Equity and contextual moderators	Gendered access to extension	Unequal access to information, inputs, land, labor, credit, and decision-making shapes extension benefits.	(Azzarri & Nico, 2022; Cavatassi et al., 2025; Murray et al., 2016; Saran et al., 2024)
	Wealth, land, and asset inequality	Farm size, asset ownership, education, and resource access influence the ability to act on advisory support.	(Aschinger et al., 2023; Holland et al., 2017; Ramilan et al., 2022; T. G. Williams et al., 2020)
	Digital access and literacy	Connectivity, phone ownership, digital literacy, language, and trust affect digital advisory use.	(Haworth et al., 2018; Njuguna et al., 2025; Ofosu et al., 2025; Porciello et al., 2022)
	Institutional trust and advisory quality	Timeliness, credibility, local relevance, and actionability determine whether farmers use extension advice.	(Khatibu & Ngowi, 2025; Nkiaka et al., 2019; Ofosu-Ampong et al., 2025; Warner et al., 2022)
	Agroecological and market context	Local ecology, infrastructure, market access, and farming-system type condition resilience outcomes.	(Descheemaeker et al., 2016; Holland et al., 2017; Lutta et al., 2024; McCord et al., 2015; Petersen-Rockney et al., 2021; Warner et al., 2022)

Note: Sources are representative examples used to support thematic coding. Several studies contributed to more than one theme or subtheme.

Supplementary Table S5. Thematic evidence map of extension-resilience pathways.

Evidence cluster	Shock type	Extension/advisory modality	Main mechanism	Resilience capacity	Main outcome	Representative studies
Climate-smart adaptation	Climate shocks	Climate-smart agriculture training; public extension; demonstrations	Knowledge translation; adaptive practice change	Adaptive capacity	CSA adoption, productivity, food security, reduced production risk	Abegunde et al. (2019); Acevedo et al. (2020); Makate et al. (2019); Wekesa et al. (2018)
Climate information use	Drought, rainfall variability, heat stress	Climate information services; weather advisory; seasonal forecasts	Risk awareness; anticipatory decision-making	Absorptive/ adaptive capacity	Better preparedness, seasonal decisions, productivity gains	Nkiaka et al. (2019); Warner et al. (2022); Khatibu et al. (2025); Tamru et al. (2025)
Farmer-led extension	Climate and livelihood shocks	Farmer extension facilitators; farmer-to-farmer learning	Peer diffusion; trust; local experimentation	Adaptive/ collective capacity	Anticipatory behavior, climate-smart practice use, local innovation	Amadu (2022); Staub and Clarkson (2021); Tambo and Wünscher (2017)
Farmer field schools	Climate shocks and livelihood stress	Farmer field schools; climate action plans	Social learning; collective problem-solving	Adaptive/ collective capacity	Improved resilience planning, farmer confidence, practice change	Pienaaah et al. (2024); Silici et al. (2021)
Digital advisory	Climate, market, and information shocks	Mobile advisory; digital agriculture services; ICT-enabled climate/agronomic advice	Rapid information delivery; personalized advice; digital decision support	Adaptive capacity	Improved access to advice, but uneven inclusion	Porciello et al. (2022); Njuguna et al. (2025); Ofosu-Ampong et al. (2025); Singh et al. (2025)
Market systems and value chains	Market and input shocks	Market-oriented extension; value-chain support; price information	Market linkage; bargaining capacity; service access	Market adaptive capacity	Income stability, market participation, reduced economic vulnerability	Kuhl (2018); Davis et al. (2021); Lutta et al. (2024)
Financial resilience	Drought, livelihood, and market shocks	Credit, insurance, savings groups, financial advisory	Financial coping; investment capacity; service linkage	Absorptive/ adaptive capacity	Perceived resilience, food security, adaptive investment	Goodwin et al. (2022); Batung et al. (2023)
Livelihood diversification	Climate and livelihood shocks	Livelihood advisory; diversification support; mixed farming advice	Risk spreading; livelihood adjustment	Livelihood adaptive capacity	Income stability, welfare improvement, reduced vulnerability	McCord et al. (2015); Mohammed et al. (2021); Ngigi et al. (2021); Ado et al. (2019)
Seed and input system resilience	Climate-induced production stress	Seed-system support; input linkage; community-based systems	Access to resilient varieties and inputs	Absorptive/ adaptive capacity	Seed security, crop resilience, reduced production disruption	Kansiime and Mastenbroek (2016); Acevedo et al. (2020)
Indigenous and local knowledge	Climate and food-security shocks	Participatory innovation; local knowledge integration	Knowledge co-production; contextual relevance	Adaptive/ transformative capacity	Locally appropriate adaptation and food-security support	Mapfumo et al. (2016); Kalidou et al. (2024)

Evidence cluster	Shock type	Extension/advisory modality	Main mechanism	Resilience capacity	Main outcome	Representative studies
Gender and inclusion	Climate, livelihood, and digital-access shocks	Gender-responsive extension; women-focused CSA; inclusive advisory systems	Empowerment; equitable access; agency	Adaptive/transformative capacity	Food security, women's empowerment, distributional resilience	Murray et al. (2016); Azzarri and Nico (2022); Saran et al. (2024); Cavatassi et al. (2025)
Compound-shock resilience	Interacting climate, market, food, and livelihood shocks	Integrated advisory systems; climate-market-livelihood support	Cross-domain coordination; institutional brokerage	Absorptive/adaptive/transformative capacity	Reduced cascading vulnerability, improved recovery, system resilience	Davis et al. (2021); Marsden et al. (2023); Michalscheck et al. (2023); Panja et al. (2026)
Resilience measurement	Multiple shock contexts	Evaluation frameworks; resilience assessment tools	Measurement of preparedness, coping, recovery, and adaptation	Absorptive/adaptive capacity	Resilience indices, vulnerability metrics, adaptive-capacity scores	Douxchamps et al. (2017); Williams et al. (2018); Ramilan et al. (2022); Michalscheck et al. (2023)
Equity-sensitive resilience	Climate and livelihood shocks	Inclusive extension, resource-sensitive advisory support	Distributional assessment; equity analysis	Adaptive/transformative capacity	Identification of who benefits and who remains vulnerable	Williams et al. (2020); Azzarri and Nico (2022); Cavatassi et al. (2025)

Note. This table summarizes thematic evidence clusters rather than quantitative frequency counts. It shows how shock type, extension modality, mechanism, resilience capacity, and outcome were linked in the synthesis.

Supplementary Table S6. Methodological and relevance appraisal framework.

Appraisal domain	High relevance/quality	Moderate relevance/quality	Low relevance/quality	Use in synthesis
Study design transparency	Design, data source, sampling, analysis, and limitations clearly reported	Design and data source reported, but some methodological details limited	Design unclear or insufficiently described	Used to assess confidence in findings
Smallholder relevance	Study directly focuses on smallholder farmers, small-scale producers, family farms, or rural farming households	Study includes smallholders within a broader farming or rural sample	Smallholder relevance indirect or weak	Used to determine eligibility and interpretability
Extension/advisory intervention clarity	Extension modality, delivery actor, advisory content, and implementation pathway clearly specified	Extension or advisory component present but partially described	Extension only mentioned superficially	Used to distinguish central vs peripheral extension evidence
Shock-context clarity	Climate, market, livelihood, or compound shock clearly identified and linked to farming/livelihood risk	Shock context implied but not fully developed	Shock context unclear or unrelated	Used to map RQ1
Mechanism clarity	Study explains how extension was identified as contributing to resilience through identifiable mechanisms	Mechanisms implied but not explicitly theorized	No clear mechanism linking extension to resilience	Used to map RQ3
Resilience-capacity clarity	Absorptive, adaptive, transformative, or related resilience capacity clearly measured or discussed	Resilience capacity partially inferable from outcomes	Resilience used vaguely or only rhetorically	Used to interpret strength of resilience claims
Outcome clarity	Outcomes directly linked to resilience, such as food security, income stability, reduced vulnerability, recovery, or resilience index	Outcomes limited to adoption, awareness, or participation	Outcomes unclear or weakly linked to resilience	Used to assess RQ4
Equity attention	Gender, wealth, landholding, age, digital access, or social position explicitly analyzed/disaggregated	Equity dimensions mentioned but not analyzed	No equity consideration	Used to assess RQ5
Contextual specificity	Agroecological, institutional, market, and livelihood context clearly described	Context partially described	Context weakly described	Used to judge transferability
Causal caution	Claims are proportional to design and acknowledge limits	Some causal language but generally cautious	Strong causal claims from weak design	Used to avoid overinterpretation
Overall review relevance	Directly addresses smallholder extension and resilience under shocks	Partially relevant to one or two core dimensions	Peripheral to the review questions	Used to prioritize evidence in synthesis

Note. The appraisal was not used to exclude studies after eligibility screening. It was used interpretively to distinguish stronger and more directly relevant evidence from weaker or more peripheral evidence when synthesizing mechanisms, resilience capacities, equity dimensions, and evidence gaps. Study-level appraisal ratings were used to guide interpretation rather than to rank or exclude studies.

Search blocks used across databases

Conceptual block	Keywords and synonyms
Agricultural extension and advisory systems	agricultural extension; rural advisory services; advisory services; farmer field schools; farmer training; farmer-to-farmer extension; farmer extension facilitators; climate information services; weather advisory services; digital advisory tools; climate-smart agriculture training; market-oriented extension; value-chain extension
Smallholder farming systems	smallholder; small-scale farmer; family farm; small-scale producer; rural household; rain-fed farming; mixed crop-livestock systems; semi-arid farming systems; farm household
Resilience capacities	resilience; adaptive capacity; absorptive capacity; transformative capacity; coping; adaptation; preparedness; recovery; vulnerability reduction; livelihood security; food security
Climate shocks	climate variability; drought; flood; cyclone; rainfall variability; heat stress; pest pressure; crop failure; water stress; soil degradation
Market and input shocks	market shock; price volatility; input-cost increase; value-chain disruption; market-access barrier; weak bargaining power; postharvest loss; demand instability
Livelihood and compound shocks	livelihood shock; income loss; labor scarcity; migration pressure; health shock; food insecurity; asset depletion; compound shock; cascading shock; COVID-19 disruption
Outcomes	adoption; productivity; yield; crop loss; income stability; livelihood diversification; food security; vulnerability reduction; resilience index; adaptive-capacity score

Purpose: This table summarizes the conceptual search blocks used to adapt database-specific Boolean strings.