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Review

Crop diversification and climate resilience in farming and rural livelihood systems: Advances, challenges, and pathways for sustainable development

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Abstract: Crop diversification can contribute to climate resilience, but improvements in soil health, biodiversity, yield, income, or diet do not demonstrate the capacity to absorb, recover from, or adapt to climatic shocks. This structured narrative review critically synthesized a corpus of 81 references spanning 2008–2026, combining foundational literature with evidence. The review focused on farm- and household-level systems and distinguished three evidence categories: direct resilience evidence, indirect evidence based on intermediate outcomes or proxies, and conceptual or mechanistic inference. Diversification generally improved ecological functions, stabilized aggregate production, broadened income and food portfolios, and could strengthen social learning. Direct evidence was narrower and concerned performance during defined adverse conditions; general yield variability and consumption smoothing under unspecified risk remain proxies. Outcomes varied with agroecological conditions, market access, farm size, labor availability, gender relations, and diversification design; competition, added labor, weak demand, and insecure access to resources could offset benefits. A refined theory of change therefore positioned enabling institutions and adaptive feedback as necessary links between diversification and resilience. Policy implications were graded by evidentiary support, and priorities were identified for longitudinal, causal, multidimensional, and gender-responsive research. Sources were compared narratively by study design, diversification practice, measured outcomes, and exposure to climatic disturbance; heterogeneous evidence precluded a pooled effect estimate.

Keywords: crop diversification; climate resilience; agroecological resilience; rural livelihoods; food and nutrition security; gender and social inclusion; evidence classification

Abbreviations: AI: artificial intelligence; LER: land equivalent ratio; LPDP: Indonesia endowment fund for education; MBILI: managing beneficial interactions in legume intercrops; n/a: not assessed; ToC: theory of change

1. Introduction

Climate change, expressed through rising temperatures, changing precipitation, and more frequent or intense extremes, threatens agricultural production and food security [1]. Resilience is therefore treated here as the capacity of linked social–ecological systems to absorb disturbance, maintain core functions, recover, adapt, and, when necessary, transform [2–5]. Crop diversification is a potential response because spatial, temporal, and genetic heterogeneity can reduce dependence on a single crop and create ecological and livelihood portfolio effects [6,7].

Vernooy [6] and related studies show that crop and varietal diversification can improve yield, income, nutrition, market access, and resource management [8–11]. These are important intermediate outcomes, but they are not equivalent to demonstrated climate resilience. Direct evidence requires observation of performance during or after a defined disturbance, such as maintained production or consumption during drought, reduced variability across adverse years, recovery time, or adaptive change [4,12–14]. This review therefore distinguishes diversification benefits from evidence of resilience.

The scope is deliberately narrower than a whole-food-system review. The primary unit of analysis is the farm or rural household, with selective attention to markets, seed systems, extension, institutions, and policy where they condition farm- and household-level outcomes. Downstream processing, retail, consumer behavior, and urban food-system logistics are outside the core evidence base. Broader cross-scale interactions provide contextual evidence for these farm- and household-level pathways [15].

This review integrates foundational work with literature available through 2026 to ask when crop diversification contributes to four linked domains: agroecological performance, economic and livelihood security, food and nutrition security, and social or institutional adaptive capacity. Each domain is interpreted as a pathway toward resilience unless a study directly observes shock absorption, recovery, adaptation, or transformation.

The synthesis addresses four questions: (1) Which diversification practices improve ecological function and aggregate yield stability? (2) Under what conditions do they stabilize income, food access, or diets during disturbance? (3) Which agroecological, market, labor, farm-size, gender, and institutional factors explain heterogeneous outcomes? and (4) How strong is the evidence linking intermediate benefits to resilience endpoints? Crop diversification is not assumed to be universally beneficial; interspecific competition, labor requirements, market limitations, and unequal control over resources can create important trade-offs [16–19].

The contribution of this review is an evidence-graded synthesis and refined theory of change that separates intermediate outcomes from demonstrated resilience, identifies boundary conditions, and distinguishes empirically supported policy implications from context-dependent recommendations and forward-looking propositions.

2. Conceptual framework: crop diversification and resilience

Diversification encompasses distinct but related strategies. Crop diversification increases the number or functional diversity of crop species through rotations, intercropping, relay cropping, or polycultures. Varietal diversification increases genetic diversity within a crop, including varietal mixtures. Mixed farming integrates crops with livestock or trees, but it is included here only when crop diversity is a material component. Livelihood diversification is broader still and may include non-farm income; it is discussed only where it interacts with crop-based risk management. These terms are not used interchangeably [20,21].

Two mechanisms anchor the ecological argument: Ecological redundancy enables species or varieties with overlapping functions to compensate when one component is impaired. The portfolio effect reduces aggregate risk because crops differ in rooting depth, resource requirements, phenology, market exposure, and stress tolerance [6]. Diversified systems may also support soil structure, nutrient cycling, pollination, and pest regulation [8,10,11,22,23]. These mechanisms justify a resilience hypothesis, but their presence alone is mechanistic or indirect evidence; resilience is demonstrated only when system performance is evaluated under disturbance.

2.1. Resilience conceptualization

This review adopts a social–ecological definition of resilience as the capacity to absorb disturbance, reorganize, adapt, or transform while maintaining essential functions and identity [5]. Ecological condition, economic resources, social organization, institutions, and vulnerability interact in shaping that capacity [24–29]. The analysis therefore distinguishes (i) intermediate outcomes, such as soil organic matter, mean yield, income level, or dietary diversity; (ii) resilience proxies, such as interannual yield variance, income volatility, consumption smoothing, or months of food shortage; and (iii) direct outcomes observed during or after a defined shock, including maintained function, recovery time, adaptive adjustment, or transformation.

Figure 1 presents the theory of change. Diversification practices generate ecological, productive, economic, nutritional, and social intermediate outcomes. Enabling conditions influence adoption and persistence, while agroecology, shock characteristics, farm size, labor and gender relations, markets, and design choices moderate effects. Intermediate outcomes may strengthen absorptive, recovery, adaptive, and transformative capacities, but this final link is conditional and often inferred rather than directly tested. Monitoring and learning create a feedback loop through which practices are redesigned.

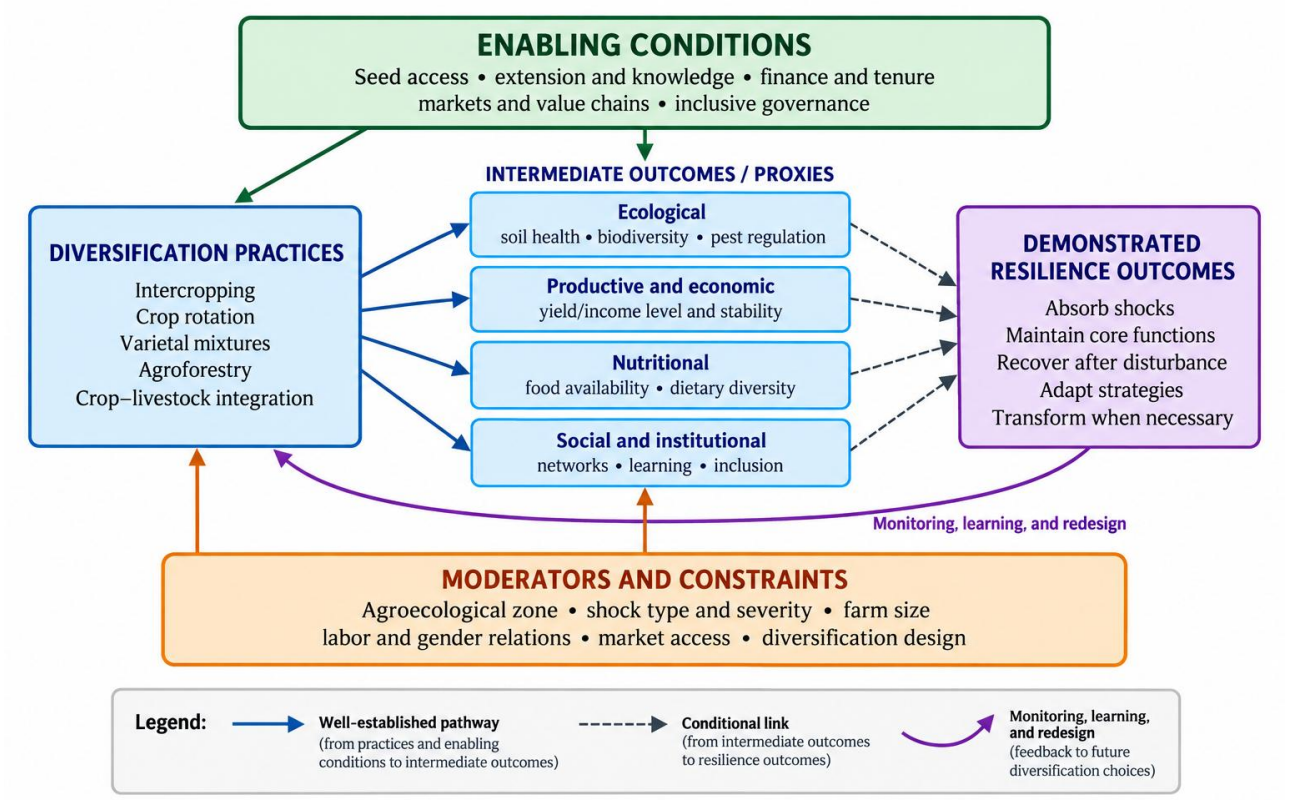


Figure 1. Evidence-sensitive theory of change linking crop diversification to climate resilience.

Solid arrows denote well-established pathways from practices and enabling conditions to intermediate outcomes. Dashed arrows denote the more conditional transition from intermediate outcomes to demonstrated resilience. Moderators and constraints affect implementation and outcomes, while monitoring, learning, and redesign create feedback to future diversification choices.

The framework prevents conceptual slippage by separating benefits from resilience endpoints. Improved soil health can increase buffering capacity; a broader crop portfolio can stabilize aggregate production or income; dietary diversity can reduce nutritional vulnerability; and networks can facilitate learning. However, resilience is established only when these capacities enable a system to maintain or regain function under disturbance or to adapt and transform in response. The same practice can therefore yield different outcomes across places and groups.

2.2. Definitional nuances and functional diversity

Functional diversity, rather than species count alone, is central to interpretation [21]. Complementary traits may improve nitrogen supply, rooting-depth distribution, phenological spread, microclimate regulation, pest suppression, or tolerance to combined heat and drought [11,16,22,30]. A cereal–legume intercrop, a sequence of crops with different water requirements, and a mixture of stress-tolerant varieties represent different mechanisms and should not be pooled without attention to purpose, design, and context.

3. Materials and methods: review approach and evidence classification

3.1. Review scope and corpus assembly

This structured narrative review examines crop diversification and climate resilience at farm and rural-household scales. Literature identification combined Vernooy's synthesis [6], targeted topic searches, and backward and forward citation chaining. The topic searches paired crop diversification with climate resilience, yield stability, income or poverty, food security or dietary diversity, gender, institutions, and policy. The corpus contains 81 references with publication years spanning 2008–2026, including empirical studies, evidence syntheses, conceptual papers, and institutional reports. Reference counts describe publications, not independent studies: the Zambia working paper [25] and journal article [31] are related reports and are interpreted together.

The review is not preregistered, and a complete record of database-specific search strings, search dates, and retrieval counts is unavailable. The search description therefore identifies the topic combinations and citation-chaining approach without claiming a reproducible systematic search or exhaustive coverage. The publication-year range describes the assembled corpus rather than a verified database search window. A supplementary source inventory (Table S1) records the role and available study characteristics of every cited publication.

3.2. Eligibility, appraisal, and synthesis

Sources were retained when crop or varietal diversification, intercropping, rotation, agroforestry, or a crop-centered mixed system was a material exposure and the source reported an ecological, productive, economic, nutritional, social, institutional, or policy-relevant outcome. Broader livelihood or food-system sources were used only when they clarified farm- or household-level mechanisms or enabling conditions. Tables 1 and 2 are illustrative evidence tables rather than an exhaustive list of all sources. Table S1 distinguishes empirical outcome studies from reviews, conceptual contributions, and contextual sources; broader policy or resilience papers are not treated as additional diversification experiments.

Sources were characterized by study design or source type, location, diversification practice, outcomes assessed, and relevance to climate resilience. For empirical studies, interpretation considered the comparator, temporal coverage, exposure to a defined disturbance, outcome scale, and treatment of confounding where these details were available. Direct evidence requires a measured outcome linked to an identified climatic shock or explicitly characterized adverse weather conditions. Interannual variability or consumption smoothing without a defined climatic contrast is classified as indirect/proxy evidence, as are soil, yield, income, and dietary improvements without a shock-response test. Conceptual/contextual sources inform mechanisms, frameworks, or enabling conditions without directly testing the diversification-to-resilience link. Missing design details are identified in Table S1 rather than inferred. These categories describe the relationship to resilience, not a formal risk-of-bias score. Heterogeneous designs and outcomes precluded a pooled effect estimate.

The synthesis is organized by ecological, economic, nutritional, and social or institutional pathways. Contradictory findings and boundary conditions are compared narratively, and policy implications are graded as evidence-supported, context-dependent, or forward-looking. Primary studies and reviews that discuss them are not interpreted as independent replications; related reports

are identified in Table S1. This approach supports qualitative comparison without converting publication counts into effect estimates or certainty scores.

3.3. Analytical pathway to resilience

The analytical pathway begins with diversification practices, proceeds through intermediate ecological and livelihood outcomes, and ends with resilience capacities or observed responses to disturbance [6]. Risk spreading may operate directly when multiple crops prevent complete production failure, whereas improved income, nutrition, or social organization may build capacity that becomes relevant only when a shock occurs [32]. The synthesis therefore treats causal links as conditional rather than automatic.

Diversification is not a universal solution. Outcomes depend on the practice, baseline system, climate hazard, resource endowment, labor and gender relations, market demand, and institutional support [12,13,18,19]. Short-term reductions in a dominant cash crop, added labor, management complexity, or weak markets may outweigh portfolio benefits. These boundary conditions are synthesized explicitly in Section 8 and Table 3.

Sections 4–7 synthesize ecological, economic, nutritional, and social pathways using the evidence categories defined above. Section 8 compares boundary conditions and evidence gaps; Section 9 refines the theory of change and research agenda; and Section 10 grades policy pathways according to the strength of support in the reviewed corpus. Section 11 sets out the limitations of the review, followed by the conclusions in Section 12.

4. Agroecological benefits and environmental resilience

Diversified cropping can improve resource-use efficiency and ecosystem services [8,22,23,33]. In this section, soil health, pest regulation, biodiversity, and mean productivity are interpreted as intermediate outcomes; multi-year yield stability under adverse weather is a resilience proxy, and performance observed during defined extremes provides stronger direct evidence. Table 1 makes this distinction explicit.

4.1. Soil fertility and structure

Legumes, deep-rooted crops, and temporally diverse rotations can increase nitrogen availability, organic inputs, soil structure, and moisture use [8,22,23,33]. In Eastern India, adding short-duration pulses after rice used residual moisture and increased annual system productivity and profitability [34]. These findings support plausible buffering mechanisms, but soil improvement or higher mean productivity should be interpreted as indirect evidence unless linked to performance during or recovery after climatic disturbance.

Table 1. Selected agroecological and economic studies, reported outcomes, and evidence classification.

Study (Location)	Diversification strategy	Yield/Production outcome	Income/Profit outcome	Ecosystem service outcome	Evidence/Ref.
Canada	Extended crop rotations (greater crop diversity vs 2-crop rotation)	Higher yield stability under weather variability; mitigated year-to-year yield swings	n/a (income stability not directly assessed)	Weather-related yield performance; ecosystem services not separately assessed here	Direct: field performance under characterized weather conditions [38]; contextual synthesis [13]
Nepal	Maize-based intercropping (maize + millet + mustard + wheat + ginger) on terraces	Land productivity increased (higher total grain yield per area); no maize yield penalty	Higher net returns per land unit	n/a (soil conservation not assessed here)	Indirect: productivity and profitability; no shock-response test [11]
Temperate regions (Northern Hemisphere)	Silvoarable agroforestry (tree + crop combinations)	Crop-yield effect not significant overall; ≈15% decline in the subgroup with tree heights >10 m and alley widths ≤96 m	n/a	Biodiversity ↑ ≈20% vs monocrop; carbon and water effects inconclusive	Indirect: biodiversity and component-yield trade-offs [16]
Global	Various forms (crop rotation, intercropping, hedgerows, etc.)	Comparable yields to monocultures (on average no yield penalty)	n/a	Multiple ecosystem services enhanced (pollination, pest control, soil health)	Indirect: ecosystem services; pooled mean outcomes [36]
Bangladesh	Mixed cropping (high Simpson Index vs low)	n/a (overall production not explicitly reported)	Farm income ↑ 2.41% per unit increase in the Simpson Diversification Index, as reported in the study abstract	n/a	Indirect: cross-sectional income association [40]
Ethiopia	Sorghum–peanut intercropping (MBILI system + vermicompost)	Sorghum yield ↑ 72 %; peanut yield restored to monocrop level; system yield ↑ and more stable	Net profit ↑ 48% under MBILI + 4.5 t/ha vermicompost; treatment-specific result	Higher LER; better resource use efficiency and reduced competition	Indirect: plot-level yield and profit under optimized design [17]
India	Crop & varietal diversification in rice-based systems (add short-season pulses/oilseeds after rice)	Higher annual system productivity from an additional crop; climate-risk reduction not directly tested	Higher profitability (added dry-season crop profits)	Improved resource use (residual moisture utilization; legume N-fixation benefits)	Indirect: annual system productivity and resource use [34]

Notes: Direct evidence links measured performance to an identified climatic disturbance or explicitly characterized adverse weather conditions. Indirect/proxy evidence includes intermediate benefits and variability measures without a defined climatic contrast. LER = land equivalent ratio; MBILI = Managing Beneficial Interactions in Legume Intercrops; n/a = not assessed.

4.2. Pest and disease regulation

Spatial and genetic heterogeneity can disrupt pest and pathogen cycles and support natural enemies [3,8,18,22,23,33]. Ugandan varietal mixtures of common bean and banana are associated with more stable perceived yields and reduced disease incidence [35], while crop genetic diversity can reduce host uniformity [3,22]. Push–pull and related intercrops illustrate how diversification can reduce pest pressure. These are strong agroecological outcomes, although their contribution to climate resilience remains indirect unless pest regulation is evaluated under climate-related disturbance.

4.3. On-farm biodiversity and ecosystem services

Crop and varietal diversity increase on-farm agrobiodiversity and can support pollination, water regulation, nutrient cycling, carbon storage, and other ecosystem services [8,36,37]. Temperate silvoarable agroforestry showed higher biodiversity on average, but crop-yield, carbon, and water outcomes varied with tree age, density, and legume inclusion [16]. Thus, ecosystem-service gains are mechanistic or indirect evidence of resilience and cannot be generalized across designs.

4.4. Yield stability and productivity

Yield stability is among the most informative resilience proxies because it evaluates performance across variable conditions. Diverse rotations have reduced weather-related yield fluctuations in long-term studies [13,38], and intercropping meta-analysis reported greater stability than monocropping [39]. Plot-scale Ethiopian evidence also shows that row configuration and soil amendment can reduce component-crop penalties while improving system yield and profit [17]. Nevertheless, higher land-equivalent ratio or mean yield without an observed climatic contrast remains an intermediate production outcome rather than direct resilience evidence.

Outcomes depend on design and context. Dense tree alleys can reduce understory yields through shade and belowground competition [16], whereas optimized spacing or legume inclusion may improve total system performance. Intercropping can raise land-equivalent ratios yet increase labor and management requirements [11,17]. Rotations may deliver stability benefits only after several seasons [38], and marketable gains depend on demand and access [40]. These contrasts show why system-level productivity, labor burden, distribution of benefits, and shock performance should be assessed together.

Overall, the agroecological literature provides strong evidence for intermediate benefits and several credible stability proxies, but fewer researchers measure recovery or adaptation following extreme events. Healthier soils, pest regulation, biodiversity, and stable aggregate yields may increase absorptive capacity; they should not be presented as definitive resilience outcomes without a disturbance-based test.

5. Economic and livelihood resilience outcomes

Economic resilience concerns the ability to maintain viable livelihoods during price and climate shocks. Diversification can spread production and market risk, but higher mean income is an intermediate outcome; reduced income variance, consumption smoothing during shocks, or faster

recovery provides stronger resilience evidence. This section evaluates the level and stability of income and the conditions that shape distributional outcomes.

5.1. Income levels and stability

Diversification can broaden markets and income sources [6,8,10,11,41–43]. In Zimbabwe, diversified smallholders showed higher crop income, cereal productivity, and food-security indicators after adjustment for observed selection factors [43]. In Nepal, intercropping increased land productivity and net returns [11]. These findings demonstrate livelihood benefits, but causal and resilience claims remain limited where studies do not observe households through a defined climatic or market shock.

Ugandan panel evidence links greater crop diversity with household welfare and consumption smoothing under risk [10], providing a stronger resilience proxy than income level alone. In Bangladesh, a higher Simpson diversity index was associated with higher annual farm income [40]; this is an economic benefit, but the cross-sectional income association does not by itself demonstrate stability or recovery.

Evidence from Kenya indicates that crop diversification can moderate climate-related income risk across heterogeneous rainfall conditions [44]. At a broader scale, mixed production portfolios can stabilize output where crop responses to rainfall differ [45]. Such portfolio effects are most credible when studies compare adverse and normal conditions or estimate variability over time; otherwise, claims should remain at the level of potential risk reduction.

5.2. Poverty reduction and livelihood improvement

Diversification is associated with lower poverty in several developing-country settings [41,46,47]. In rural Ghana, crop diversity was linked to lower multidimensional poverty [47], while perennial-crop production was associated with higher income and food expenditure [48]. Ethiopian panel analysis also found links between agricultural diversity and poverty transitions [41]. These studies support a livelihood pathway to adaptive capacity, but poverty reduction should be distinguished from direct evidence of response to climate shocks.

5.3. Market integration and value-chain development

Diversification may expand access to higher-value or differentiated markets. Examples from Kenya and other smallholder settings show that combining staples with horticultural or underutilized crops can broaden revenue sources [6,23,49,50]. However, gains depend on demand, storage, processing, transport, bargaining power, and control over income. Where these conditions are weak, diversification can add production and marketing costs without stabilizing returns.

5.4. Risk management (natural insurance)

Crop diversification can function as natural insurance when crop responses to weather and prices are imperfectly correlated [12,24,50,51]. Farmers' risk perceptions and available management options also shape adoption choices [52]. Tanzanian households using traditional diversified practices reported

less food rationing during extreme weather, providing direct evidence for consumption buffering [53]. By contrast, many cross-sectional studies identify risk-management motives but cannot establish whether diversification caused resilience.

Formal insurance and diversification can be complements or substitutes. In Borana, insured pastoral households were less likely to add crop cultivation, whereas training, cooperative participation, and infrastructure supported livelihood diversification and food security [54]. The result cautions against assuming that every additional activity improves resilience and highlights the importance of institutional context.

Economic evidence therefore ranges from indirect associations with income and poverty to stronger observations of consumption smoothing and climate-risk buffering. Table 2 distinguishes these levels. The next section examines food and nutrition outcomes using the same evidentiary rule.

Table 2. Selected food-security, nutrition, and social studies, reported outcomes, and evidence classification.

Study (Location)	Diversification strategy	Food security/Nutrition outcome	Poverty/Livelihood outcome	Resilience/Adaptive capacity outcome	Evidence/Ref.
Malawi	Mixed cropping and crop rotation (maize–legume combinations) among smallholders	Improved household food security (more months of food self-sufficiency); diversified farms experienced fewer hungry seasons	n/a (poverty not directly assessed)	Food-security benefit; climate-shock response not directly established	Indirect: cross-sectional food-security association [42]
Malawi	Participatory agroecological diversification (legume intercrops, doubled-up legumes)	Increased dietary diversity and nutrient-rich food consumption	n/a (income effect not established here)	Food and dietary benefits relevant to adaptive capacity; no direct shock-response test	Indirect: intervention improved food security and diet diversity [9]
Ethiopia (Borana)	Livelihood diversification (crop cultivation integrated with livestock)	Enhanced household food security; diversified households significantly less food-insecure	n/a (poverty not directly assessed, but diversification correlated with improved welfare)	Food-security association; recovery from drought not directly tested	Indirect: observational livelihood-diversification association [54]
Ghana	Multi-crop farming (measured via crop diversity index)	n/a (focus on poverty reduction)	Significantly lower multidimensional poverty across health, education, and living standards dimensions	Reduced deprivation is relevant to capacity; resilience remains inferred	Indirect: poverty association; resilience inferred [47]

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Study (Location)	Diversification strategy	Food security/Nutrition outcome	Poverty/Livelihood outcome	Resilience/Adaptive capacity outcome	Evidence/Ref.
Tanzania	Traditional crop diversification and intercropping of indigenous drought-tolerant crops (e.g., sorghum)	Higher dietary diversity during climate shocks; diversified households required less food rationing during droughts	n/a (income not assessed here)	Food consumption and coping assessed during extreme weather; causal interpretation depends on design	Direct: food consumption and coping during extreme weather [53]
Uganda	Polyculture farming (diverse crop portfolios, household survey)	Household welfare and consumption smoothing under risk	Higher household welfare; income recovery not separately established here	Consumption-smoothing proxy; climate-specific nutrition maintenance not established here	Indirect/proxy: panel evidence of consumption smoothing under risk [10]
Zimbabwe	Mixed cropping and crop–livestock systems among smallholders	Higher household food security and better nutrition indicators	Higher household crop income; poverty reduction not established by this table entry	Livelihood benefits relevant to capacity; direct shock response not established	Indirect: livelihood and food-security associations [43]
Kenya/Sub-Saharan Africa (conceptual)	General smallholder diversification (conceptual synthesis)	n/a	n/a	Emphasized as a core strategy for smallholder resilience against climate-induced food insecurity	Conceptual/contextual synthesis [81]

Notes: Evidence classification concerns the diversification-to-resilience link, not the general quality of the study. Direct evidence observes outcomes in relation to a defined climatic shock; indirect/proxy evidence includes associated welfare, capacity, or consumption smoothing without a specified climatic contrast. Conceptual evidence proposes a mechanism without testing a resilience endpoint. n/a = not assessed.

6. Nutritional and food security resilience outcomes

Food and nutrition outcomes are central to household welfare and link farm diversity with healthy diets [55,56], but nutritional resilience means maintaining or recovering adequate food access and diet quality during disturbance. Greater production, food-consumption scores, or dietary diversity in normal conditions are intermediate outcomes. Evidence is stronger when a study observes food intake, rationing, or diet stability during climate or market shocks.

6.1. Food availability and caloric security

Diversification can increase farm food availability and reduce seasonal dependence on one staple. In Malawi, diversified households have better food-security indicators and fewer hungry months [42]. Kenyan and Nigerian evidence similarly links broader crop portfolios with food availability under climate risk [44,57]. These findings support a buffering pathway, although study designs differ in their ability to identify causal shock responses.

In Borana, households combining livestock with crop or other livelihood activities had better food-security indicators, and livelihood diversification is strongly correlated with food security [54]. Because the study is observational, the result is interpreted as indirect evidence relevant to adaptive capacity rather than proof that diversification causes recovery from drought.

6.2. Dietary diversity and nutrition

Crop diversification can improve dietary quality by increasing access to legumes, vegetables, fruits, and nutrient-dense varieties. Participatory legume diversification in Malawi improved household food security and dietary diversity [9], while farmers in the Bolivian Altiplano value diverse potato and quinoa varieties as buffers against frost and drought [58]. These outcomes strengthen nutritional capacity, but only observations made during a defined disturbance demonstrate nutritional resilience directly.

Diversification can improve access to nutrient-dense crops, but nutritional effects depend on the crop, consumption patterns, and supporting interventions. In a randomized controlled effectiveness study in rural Mozambique, an intervention promoting orange-fleshed sweet potato production and consumption increased vitamin A intake among children and women [59]. The intervention combined agricultural support, nutrition-related behavior change, and marketing; the finding does not isolate the effect of adding a crop to a cereal-based system or establish resilience to climatic shocks. Mabhaudhi et al. [60] discuss the nutritional and stress-tolerance potential of underutilized crops, while Meldrum et al. [49] describe initiatives involving Bambara groundnut, fonio, and native vegetables in Mali. These sources support a nutrition pathway, but do not justify a general claim that all such crops have superior nutrient profiles or that their integration necessarily increases mineral intake.

6.3. Coping with shocks—Nutritional dimension

Tanzanian evidence provides one of the clearer direct links: Households using traditional diversification, including indigenous drought-tolerant crops, maintain higher dietary diversity and use less food rationing during extreme weather than less-diversified households [53]. Ugandan panel evidence on consumption smoothing under risk offers a complementary resilience proxy [10]. Such designs are more informative than cross-sectional comparisons conducted only under normal conditions.

Community seed and food exchange can complement household diversification by improving access to planting material and food [6,61]. Community Biodiversity Management provides an institutional approach to maintaining crop diversity and supporting collective learning [61], while social-network research in northern Ghana links social relationships with adaptive capacity [62]. These sources support plausible mechanisms for mutual assistance; they do not establish that community biodiversity management prevents famine or guarantees adequate nutrition during climate crises.

6.4. Public health and nutrition synergy

Agricultural biodiversity can support dietary diversity and food and nutrition security. Frison et al. [63] identified pathways through the availability, use, and conservation of diverse foods. This provides a rationale for protecting nutrient-rich crop portfolios as climate conditions change, but does

not establish a uniform reduction in micronutrient deficiencies across regions. Nutrient intake and health outcomes require direct measurement.

Nutritional outcomes also interact with livelihood conditions. Income from diversified production may support food purchases, but this pathway depends on market access, prices, and household allocation [10,55,56]. Higher production or income therefore need not translate into a balanced diet. Evaluating food availability together with dietary quality and shock exposure provides a more informative test of nutritional resilience.

Taken together, the reviewed evidence supports a plausible pathway from crop diversity to food availability and dietary quality, but direct evidence of maintaining nutrition through shocks is concentrated in a limited number of settings. Table 2 therefore labels food-security and nutrition findings as direct, indirect/proxy, or conceptual rather than treating all positive outcomes as equivalent.

7. Social and institutional dimensions of resilience

Social networks, knowledge exchange, inclusive decision-making, and institutions can enable adoption and adaptive adjustment. They are best interpreted as capacities or moderators unless a study demonstrates how they change outcomes during or after a disturbance. Therefore, this section distinguishes social enabling conditions from observed resilience outcomes.

7.1. Social capital and networks

Farmer groups, extension linkages, and seed-exchange networks can support experimentation and access to planting material. In northern Ghana, network participation is associated with adaptive decisions [62]. Community seed banks and biodiversity committees can also distribute risk by maintaining locally adapted varieties [22,61]. These mechanisms strengthen adaptive capacity, but their effect depends on network inclusiveness, resource access, and the type of shock.

Vernooy [6] emphasizes that cooperatives, local organizations, and seed networks can reinforce diversification. Their contribution is reciprocal: Institutions enable diversification, while collective experimentation and exchange may strengthen social capital. The framework therefore represents social organization as both an enabling condition and an intermediate outcome, with a feedback loop rather than a one-way causal chain.

7.2. Gender and inclusion

Gender relations determine who supplies labor, selects crops, controls land and income, and receives benefits. Women often manage home gardens, seed selection, legumes, and vegetables, while men may control cash-crop decisions. These patterns vary by context and can either support or constrain diversification [19,64,65].

In Bangladesh, women's decision-making authority is associated with farmland allocation and crop diversification [64]. Gender-responsive climate services and extension can improve access to adaptation options [66], while gender- and nutrition-focused communication provides relevant contextual evidence on protecting diet quality during shocks [67]. However, diversification may increase unpaid labor or shift control of profitable crops away from women. Gender-disaggregated analysis is therefore necessary before equity or resilience gains are claimed.

A strategic review documents persistent gender gaps in agrifood governance and recommends gender-responsive extension, participatory seed programs, and women's organizations [68]. These recommendations are relevant enabling propositions; evidence of impact should be evaluated separately from evidence that programs merely reach participants.

7.3. Local knowledge and cultural context

Local knowledge shapes crop choice, timing, varietal mixtures, and risk interpretation. Intercropping in Java's karst landscapes illustrates how locally adapted practices support production under resource constraints [69], while participatory varietal selection in Uganda improves the fit and acceptance of crop mixtures [35]. Co-production can strengthen adoption, but traditional status alone does not establish resilience; performance must still be assessed against relevant hazards and outcomes.

Cultural preferences and established cropping practices can influence the acceptability of diversification. Evidence from rice-dominated Sri Lankan systems [70] and farmers' perceptions in the Bolivian Altiplano [58] indicates that crop choice must be understood within local livelihood priorities and constraints. Participatory assessment can identify acceptable options and relevant trade-offs, but cultural recognition alone does not demonstrate improved performance under climate stress.

7.4. Institutions and governance

Institutions influence seed availability, extension priorities, incentives, procurement, and market access. The reviewed literature indicates that diversification is easier to sustain when farmers can obtain appropriate seed, information, infrastructure, extension support, and outlets for secondary crops [6,25,50,71–73]. Conversely, policies centered on a narrow set of staples or export crops may raise the opportunity cost of diversification.

Governance evidence is less direct than plot- or household-level evidence. Reviews stress that extension and multi-level coordination affect adaptation options [57, 68], while cross-scale synthesis shows that plot, farm, landscape, value-chain, and policy processes must interact [15]. These findings support institutional enabling conditions, not a claim that any single governance intervention guarantees resilience.

Global assessments connect agrobiodiversity with ecosystem services and sustainable food production [63,74]. Country and historical analyses also suggest that political leadership can shape agricultural transformation [75]. Because these sources operate at different scales and use different designs, the review treats them as contextual support rather than direct tests of farm-level climate resilience.

Social and institutional factors therefore moderate who can diversify, how benefits are distributed, and whether learning continues after a shock. Strong networks and inclusive institutions may amplify ecological and livelihood pathways; exclusion, insecure tenure, weak markets, or monoculture-oriented incentives can suppress them. Evidence remains uneven, particularly for causal and gender-disaggregated outcomes.

8. Knowledge gaps and challenges in linking diversification to resilience

The evidence base is strongest for intermediate agroecological and livelihood outcomes and weaker for recovery, adaptation, and transformation after defined climate shocks. The gaps below are organized around evidence type, measurement, heterogeneity, equity, policy, time horizon, and causal inference.

(i) Direct resilience evidence. Few researchers follow diversified and less-diversified farms or households through comparable climatic disturbances. Studies of consumption during extreme weather and multi-year yield stability are informative [38,53], but wider replication is needed. Cross-sectional gains in yield, income, or diet should remain classified as intermediate outcomes.

(ii) Multidimensional measurement. Resilience spans ecological, economic, nutritional, social, and institutional dimensions, yet most researchers examine one domain [12,57]. Composite indices can broaden measurement [76,77], but weighting, validation, and scale sensitivity require scrutiny. A shared core should include shock exposure, maintenance of function, recovery time, adaptive change, and distributional outcomes.

(iii) Boundary conditions and trade-offs. Effects vary with hazard, agroecology, market access, farm size, labor and gender relations, and diversification design [16–19,40]. Table 3 synthesizes when benefits are more plausible and when diversification may underperform. This comparison clarifies that the relevant question is not simply whether to diversify, but what to diversify, for which objective, under which constraints, and for whom [21].

(iv) Gender and social equity. Many studies lack sex-disaggregated labor, control, and benefit measures [19,64,65]. Thus, researchers should test who bears added management costs, who controls income, and whether diversification changes intra-household food allocation. Equity should be measured as an outcome, not assumed from participation.

(v) Policy and political economy. Evidence on seed, extension, market, subsidy, procurement, and tenure policies is fragmented. Reviews reveal plausible enabling mechanisms [15,50,57,68], but few studies compare policy designs or estimate causal effects at scale. Micro-level evidence should therefore not be translated automatically into universal policy prescriptions.

(vi) Long-term and transgenerational effects. Resilience may accumulate through soil improvement, learning, and seed conservation, but most studies are short or medium term. Longitudinal designs are needed to detect delayed benefits, persistence, recovery, and possible downsides such as labor fatigue, market saturation, or poorly designed rotations.

(vii) Causal inference and comparability. Observational studies are vulnerable to selection bias because more capable or better-resourced farmers may be more likely to diversify. Panel, experimental, and quasi-experimental designs can improve attribution, while common definitions of diversity, shock exposure, and resilience outcomes would support comparison and future meta-analysis [12,53].

These gaps require claims to be calibrated to study design and evidence type. The refined theory of change in Section 9 uses conditional pathways and explicit feedback rather than assuming that every positive diversification outcome culminates in resilience.

Table 3. Boundary conditions explaining heterogeneous diversification outcomes.

Contextual factor	Conditions favoring benefits	Conditions associated with underperformance	Analytical or design implication
Agroecology and hazard	Complementary rooting, phenology, or stress tolerance matches the dominant hazard.	Competition for light, water, or nutrients; benefits assessed under hazards different from those faced.	Select traits and arrangements for the locally relevant drought, flood, heat, pest, or rainfall-variability profile [16,17,38].
Market conditions	Reliable demand, storage, processing, information, and transport for multiple crops.	Thin markets, price penalties, perishability, or high transaction costs.	Pair production diversity with crop-specific value-chain diagnosis [15,40,50].
Labor and gender	Labor calendars are complementary and women or marginalized groups share decisions and benefits.	Peak-season labor bottlenecks, unpaid workload, or loss of control over profitable crops.	Measure labor by season and sex, decision authority, and control of revenue [19,64,65].
Farm size and resources	Sufficient land, seed, knowledge, liquidity, and equipment permit experimentation.	Very small holdings or scarce capital make added enterprises costly or risky.	Use phased, low-cost options and avoid one-size-fits-all diversity targets [18,23,70].
Diversification type and design	Functional complementarity, suitable density, sequence, and spatial arrangement.	Species count rises without functional complementarity; shading or crop-level yield penalties dominate.	Evaluate system yield, stability, input use, and component-crop trade-offs together [11,16,17,21].
Institutions and risk instruments	Plural seed systems, extension, cooperatives, tenure security, and complementary insurance.	Monoculture-oriented incentives or formal insurance substitutes for ex-ante risk reduction.	Test interactions among institutions rather than assuming additive effects [15,54,57,71].

Note: Conditions are synthesized from the reviewed corpus and should be treated as testable moderators, not deterministic rules.

9. Refining the theory of change and methodological innovations

The theory of change integrates the evidence distinctions and boundary conditions identified above. It retains Vernooy's [6] portfolio and livelihood pathways while making enabling conditions, moderators, feedback, and measurable resilience endpoints explicit.

9.1. Refined theory of change

Improved access to crops and varieties can enable farmers to redesign production, producing ecological and livelihood outcomes [6]. Whether those outcomes become resilience depends on their interaction, distribution, persistence, and relevance to a specific disturbance. The framework therefore rejects a linear assumption that any single benefit is sufficient.

(i) Enabling conditions and feedback. Seed access, knowledge, markets, finance, tenure, institutions, and social networks influence adoption and persistence [6,15,32,50,71]. Monitoring and learning provide feedback that informs adjustments to crop choice, spatial arrangement, and timing.

(ii) Resilience as the endpoint. Outcomes should be linked to absorptive capacity (maintaining function), recovery, adaptive adjustment, or transformation [5,26]. Yield or income level alone is insufficient; relevant indicators include variability under stress, consumption smoothing, recovery time, strategy change, and avoidance of damaging coping responses.

(iii) Trade-off management. Diversification design must balance production, income, nutrition, labor, and ecosystem objectives [12–14,16,17]. Participatory monitoring can identify unintended effects and support staged or context-specific adjustment.

(iv) Social and distributional pathways. Networks, collective marketing, seed exchange, and women's decision-making may strengthen adaptive capacity [6,61,64]. These effects are conditional: participation, workload, control over benefits, and institutional responsiveness determine whether social outcomes are inclusive.

Refined ToC summary: Farmers use diverse seed, knowledge, and enabling support to implement context-appropriate practices. These practices generate intermediate ecological, productive, economic, nutritional, and social outcomes. Moderators determine the magnitude and distribution of those outcomes. Resilience is demonstrated when combined capacities help the system absorb, recover from, adapt to, or transform in response to disturbance. Monitoring, learning, and redesign complete the feedback loop.

9.2. Methodological recommendations

Testing the refined ToC requires designs that connect practices to intermediate outcomes and then to disturbance-specific endpoints. A participatory sequence can identify goals, characterize hazards, co-design options, monitor implementation, and evaluate causal pathways [6,78].

1. Identify Goals and Challenges: Analyze farmer goals, livelihoods, and existing diversity, ensuring gender/social differentiation.
2. Assess Climate Risks: Evaluate local and projected climate risks using tools like climate analog analysis or vulnerability mapping [79].
3. Co-design Diversification Options: Collaboratively design options integrating farmer knowledge and improved germplasm, addressing how to diversify and why [8,21,25,57,64,65,80].
4. On-farm Implementation and Monitoring: Implement options with iterative learning, monitoring yields, labor, diet, and income.
5. ToC-based evaluation: Test whether intermediate outcomes mediate shock absorption, recovery, adaptation, or transformation, and identify where the causal chain fails [6,53].

(i) Integrated indicators. A minimum set should record diversification type and intensity, hazard exposure, baseline vulnerability, soil or ecosystem function, yield and income variability, diet and food-security stability, recovery time, social organization, and gender-disaggregated labor and control. Consistent measurement would improve comparability.

(ii) Causal and longitudinal designs. Randomized, phased-rollout, matched-panel, difference-in-differences, or instrumental-variable approaches can strengthen attribution where appropriate. Repeated observations before, during, and after climatic events are especially valuable because resilience cannot be inferred from a single normal-season outcome.

(iii) Mixed-method and participatory evaluation. Quantitative measures can estimate variability and recovery, while interviews and process tracing explain how households cope, learn, or change

strategies. *Qualitative evidence* should be analyzed systematically and triangulated rather than used only as illustration.

(iv) Scaling and policy evaluation. Comparative policy pilots should test seed-system, extension, market, finance, and procurement interventions across contexts. Evaluation should include adoption, persistence, distributional effects, unintended consequences, and resilience endpoints, not only area planted or short-term yield.

The ToC and research agenda therefore shift attention from cataloguing benefits to testing conditional causal pathways. This approach can show when diversification delivers resilience, when it produces only intermediate gains, and when constraints prevent benefits.

10. Policy implications and pathways for scaling diversification under climate risk

Policy implications should be proportional to evidence. Table 4 separates actions supported consistently in the corpus, context-dependent recommendations that require local adaptation, and forward-looking propositions that warrant pilot testing. This grading concerns the diversification-to-resilience pathway, not the general desirability of each policy.

Table 4. Evidentiary status of policy pathways.

Evidence tier	Policy pathway	Basis in the reviewed evidence	Use and caveat
Evidence-supported	Access to appropriate seed and knowledge; whole-farm extension; explicit inclusion of diversification as an adaptation option.	Repeated empirical and synthesis support for adoption and intermediate outcomes.	Specify hazard and objective; monitor resilience endpoints [6,15,22,66,71].
Context-dependent	Market/value-chain support; gender-responsive delivery; cooperative and infrastructure support.	Benefits vary with crop, location, bargaining power, workload, and resource access.	Diagnose local constraints and distributional effects before scaling [19,40,50,54,64].
Forward-looking	Diversification-linked finance or insurance; procurement incentives; land-use targets; resilience-index-based funding.	Plausible mechanisms but limited comparative causal evidence in this corpus.	Use pilots with counterfactuals, cost analysis, safeguards, and validated indicators [12,26,76].

Note: The tiers indicate evidentiary support for a climate-resilience effect, not whether an intervention may have other social or environmental benefits.

10.1. Integrating diversification into climate adaptation and food security policies

Evidence-supported direction: Integrate crop and varietal diversification into adaptation and food-security planning as an option rather than a universal prescription [6,15,25,31]. Programs should define the hazard, objective, target group, and expected resilience endpoint, then monitor whether diversification maintains function or supports recovery.

10.2. Supportive seed systems and genetic resource policies

Evidence-supported direction: Improve access to diverse, locally appropriate seed through plural formal and community-based systems [22,71]. Participatory selection and small diversity kits can support experimentation, but seed provision should be paired with agronomic guidance, quality assurance, and monitoring of who can access and control the material.

10.3. Facilitating market development and value-chain support

Context-dependent recommendation: Develop storage, processing, procurement, information, and value-chain arrangements for secondary and underutilized crops [15,40,49,50]. Market support is essential where farmers would otherwise face low demand or high transaction costs; the appropriate instrument depends on crop, location, scale, and bargaining conditions.

10.4. Innovative financial and risk mitigation instruments

Forward-looking proposition: Pilot financial products that recognize portfolio effects, including diversification grants, flexible credit, or insurance designs compatible with mixed cropping. These instruments are *plausible but* not strongly evaluated in the reviewed corpus and should be tested for additionality, moral hazard, distributional effects, and interaction with existing self-insurance.

Financial support should complement rather than displace on-farm risk management. Evidence from Borana suggests that insurance and diversification decisions may substitute under some conditions, while training, cooperatives, and infrastructure can facilitate diversification [54]. Program design should therefore be evaluated locally.

10.5. Reorienting extension and education services

Evidence-supported direction: Reorient extension from single-crop yield maximization toward whole-farm objectives, including soil function, risk, diet, labor, and markets [57,66,68]. Advice should remain crop- and context-specific, and gender-responsive delivery should measure access, workload, decision-making, and benefits.

10.6. Strategic land use and crop procurement policies

Forward-looking proposition: Use public procurement, school feeding, or land-use pilots to create demand for suitable crops and landscape mosaics. The reviewed corpus provides a plausible rationale but limited comparative evidence on instrument design. Pilots should assess cost, market displacement, farmer inclusion, nutrition, and resilience outcomes before scaling.

10.7. Ensuring gender and social inclusion in policy design

Context-dependent recommendation: Incorporate gender and social inclusion into seed, extension, finance, and market interventions [19,64,65,68]. Programs should protect land and resource access,

avoid increasing unpaid labor, include marginalized groups in crop selection, and track who controls new income and food.

10.8. Establishing robust monitoring and evaluation for resilience

Forward-looking proposition: Complement production indicators with disturbance-sensitive metrics such as yield and income variance, food rationing during shocks, recovery time, adaptive strategy change, and distributional effects. Indicator sets should be piloted and validated before they are used for funding or performance targets [12,26,76].

11. Limitations of the review

This structured narrative review offers an interpretive synthesis rather than exhaustive coverage of the literature. Iterative searches and citation chaining can favor well-connected publications, and an incomplete search log limits independent reproduction of the corpus. Publication and availability biases may also favor positive or readily accessible findings. The source inventory improves transparency about coverage and study characteristics, but cannot substitute for a preregistered search and screening process.

The evidence combines field experiments, observational household studies, reviews, conceptual contributions, and policy reports. These sources differ in diversification measures, comparators, time horizons, geographic scale, and outcome definitions. Some publications draw on overlapping primary studies or represent related reports; consequently, the number of references is not the number of independent tests. A formal risk-of-bias assessment and meta-analysis are not conducted. Residual confounding and selection into diversification constrain causal interpretation, especially in cross-sectional studies.

The distinction between direct, indirect/proxy, and conceptual/contextual evidence is an analytical classification rather than a validated certainty rating. Yield stability and consumption smoothing are informative, but are not equivalent to measured recovery, adaptation, or transformation after an identified climate shock. Study-design details are incomplete for some sources, and nutritional, gender-disaggregated, and long-term recovery outcomes remain unevenly documented. Findings therefore support context-specific interpretation and testable pathways rather than universal effect sizes. The emphasis on farms and rural households also limits transfer to downstream processing, retail, and urban food systems.

12. Conclusions

Crop diversification can strengthen ecological function, production portfolios, livelihoods, diets, and social learning, but these benefits occupy different positions in the causal pathway to climate resilience. The reviewed corpus provides strong support for many intermediate outcomes and credible evidence for yield stability, consumption smoothing, and food-intake buffering in several settings. Evidence of recovery, adaptation, and transformation after defined climate shocks remains limited.

Effects are heterogeneous. Agroecology, hazard type, diversification design, farm size, labor and gender relations, markets, seed access, and institutions can amplify or reverse benefits. The theory of

change therefore treats resilience as a conditional outcome produced by interacting capacities, enabling conditions, and feedback, rather than as an automatic consequence of greater crop diversity.

Policy should prioritize context diagnosis, access to appropriate seed and knowledge, market and institutional support, inclusive design, and disturbance-sensitive monitoring. Financial incentives, procurement, and land-use measures are promising but require comparative pilots. In future studies, researchers should use longitudinal and causal designs, multidimensional indicators, and gender-disaggregated analysis to establish when diversification helps farms and rural households absorb, recover from, adapt to, or transform under climate stress.

Use of Generative-AI tools declaration

The authors declare that ChatGPT (OpenAI) and Paperpal were used for brainstorming, outlining, language editing, and manuscript formatting. All AI-assisted text was reviewed and revised by the authors; no research data were generated or modified using AI, and all citations and factual statements were independently verified.

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Conflict of interest

The authors have no relevant financial or non-financial interests to disclose.

Authors' contributions

Alfina Handayani: Conceptualization; methodology; data curation; formal analysis; software; visualization; writing—original draft; writing—review and editing. Jamhari: Supervision; methodology refinement; validation; writing—review and editing. Jangkung H. Mulyo: Supervision; resources; validation; writing—review and editing. Arini W. Utami: Supervision; investigation; data collection; resources; writing—review and editing. All authors read and approved the final manuscript.

References

1. Terán F, Vives-Peris V, Gomez-Cadenas A, et al. (2024) Facing climate change: Plant stress mitigation strategies in agriculture. *Physiol Plant* 176: e14484. https://doi.org/10.1111/ppl.14484
2. Folke C (2016) Resilience (Republished). *Ecol Soc* 21: 44. https://doi.org/10.5751/ES-09088-210444
3. Hajjar R, Jarvis DI, Gemmill-Herren B (2008) The utility of crop genetic diversity in maintaining ecosystem services. *Agric Ecosyst Environ* 123: 261–270. https://doi.org/10.1016/j.agee.2007.08.003

4. Béné C (2020) Resilience of local food systems and links to food security—A review of some important concepts in the context of COVID-19 and other shocks. *Food Secur* 12: 805–822. https://doi.org/10.1007/s12571-020-01076-1
5. Folke C, Carpenter SR, Walker B, et al. (2010) Resilience thinking: Integrating resilience, adaptability and transformability. *Ecol Soc* 15: 20. https://doi.org/10.5751/ES-03610-150420
6. Vernooy R (2022) Does crop diversification lead to climate-related resilience? Improving the theory through insights on practice. *Agroecol Sustain Food Syst* 46: 877–901. https://doi.org/10.1080/21683565.2022.2076184
7. Hansen J, Hellin J, Rosenstock T, et al. (2019) Climate risk management and rural poverty reduction. *Agric Syst* 172: 28–46. https://doi.org/10.1016/j.agsy.2018.01.019
8. Beillouin D, Ben-Ari T, Makowski D (2019) Evidence map of crop diversification strategies at the global scale. *Environ Res Lett* 14: 123001. https://doi.org/10.1088/1748-9326/ab4449
9. Bezner Kerr R, Kangmennaang J, Dakishoni L, et al. (2019) Participatory agroecological research on climate change adaptation improves smallholder farmer household food security and dietary diversity in Malawi. *Agric Ecosyst Environ* 279: 109–121. https://doi.org/10.1016/j.agee.2019.04.004
10. Tesfaye W, Tirivayi N (2020) Crop diversity, household welfare and consumption smoothing under risk: Evidence from rural Uganda. *World Dev* 125: 104686. https://doi.org/10.1016/j.worlddev.2019.104686
11. Chapagain T, Pudasaini R, Ghimire B, et al. (2018) Intercropping of maize, millet, mustard, wheat and ginger increased land productivity and potential economic returns for smallholder terrace farmers in Nepal. *Field Crops Res* 227: 91–101. https://doi.org/10.1016/j.fcr.2018.07.016
12. Ansah IGK, Gardebroek C, Ihle R (2019) Resilience and household food security: a review of concepts, methodological approaches and empirical evidence. *Food Secur* 11: 1187–1203. https://doi.org/10.1007/s12571-019-00968-1
13. Gil JDB, Cohn AS, Duncan J, et al. (2017) The resilience of integrated agricultural systems to climate change. *Wiley Interdiscip Rev Clim Change* 8: e461. https://doi.org/10.1002/wcc.461
14. Kozicka M, Gotor E, Pagnani T, et al. (2024) Examining linkages among multiple sustainable development outcomes: does the productive safety net program increase on-farm agrobiodiversity? *Environ Dev Sustain* 26: 15429–15449. https://doi.org/10.1007/s10668-023-03257-2
15. Reckling M, Watson CA, Whitbread A, et al. (2023) Diversification for sustainable and resilient agricultural landscape systems. *Agron Sustain Dev* 43: 44. https://doi.org/10.1007/s13593-023-00898-5
16. Choden T, Lindhardt MKK, Hofmeijer M, et al. (2026) Tree-crop combinations and their variable effects on agroecosystem services: A systematic review and meta-analysis of temperate silvoarable agroforestry in the Northern Hemisphere. *Agric Ecosyst Environ* 396: 109963. https://doi.org/10.1016/j.agee.2025.109963
17. Ebbisa AF, Dechassa N, Bekeko Z, et al. (2024) Modifying row-configuration and vermicompost application reduces intercropped peanut (*Arachis hypogaea* L.) yield instability and penalty in sorghum at Babile, Eastern Ethiopia. *Heliyon* 10: e35662. https://doi.org/10.1016/j.heliyon.2024.e35662
18. Kozicka M, Gotor E, Ocimati W, et al. (2020) Responding to future regime shifts with agrobiodiversity: A multi-level perspective on small-scale farming in Uganda. *Agric Syst* 183: 102864. https://doi.org/10.1016/j.agsy.2020.102864

19. Chanana-Nag N, Aggarwal PK (2020) Woman in agriculture, and climate risks: Hotspots for development. *Clim Change* 158: 13–27. https://doi.org/10.1007/s10584-018-2233-z
20. Lin BB (2011) Resilience in agriculture through crop diversification: Adaptive management for environmental change. *BioScience* 61: 183–193. https://doi.org/10.1525/bio.2011.61.3.4
21. Hufnagel J, Reckling M, Ewert F (2020) Diverse approaches to crop diversification in agricultural research: A review. *Agron Sustain Dev* 40: 14. https://doi.org/10.1007/s13593-020-00617-4
22. Jarvis DI, Hodgkin T, Sthapit BR, et al. (2011) An heuristic framework for identifying multiple ways of supporting the conservation and use of traditional crop varieties within the agricultural production system. *Crit Rev Plant Sci* 30: 125–176. https://doi.org/10.1080/07352689.2011.554358
23. McCord PF, Cox M, Schmitt-Harsh M, et al. (2015) Crop diversification as a smallholder livelihood strategy within semi-arid agricultural systems near Mount Kenya. *Land Use Policy* 42: 738–750. https://doi.org/10.1016/j.landusepol.2014.10.012
24. Asfaw S, Pallante G, Palma A (2018) Diversification Strategies and Adaptation Deficit: Evidence from Rural Communities in Niger. *World Dev* 101: 219–234. https://doi.org/10.1016/j.worlddev.2017.09.004
25. FAO (2016) Diversification under climate variability as part of a CSA strategy in rural Zambia. ESA Working Paper 16-07. Rome: FAO. Available from: https://www.fao.org/agrifood-economics/publications/detail/en/c/450250/.
26. Owen G (2020) What makes climate change adaptation effective? A systematic review of the literature. *Glob Environ Chang* 62: 102071. https://doi.org/10.1016/j.gloenvcha.2020.102071
27. Vernooy R, Vongkhamsao V (2015) Introduction: Identifying effective policy measures for crop diversification. In: Vernooy R (Ed.), *Effective Implementation of Crop Diversification Strategies for Cambodia, Lao PDR and Vietnam: Insights from Past Experiences and Ideas for New Research,* Rome: Bioversity International, 1–7. Available from: https://hdl.handle.net/10568/68388.
28. Tanner T, Lewis D, Wrathall D, et al. (2015) Livelihood resilience in the face of climate change. *Nat Clim Chang* 5: 23–26. https://doi.org/10.1038/nclimate2431
29. Córdoba Vargas CA, Hortúa Romero S, León Sicard T (2020) Key points of resilience to climate change: a necessary debate from agroecological systems. *Clim Dev* 12: 564–574. https://doi.org/10.1080/17565529.2019.1664376
30. Nelimor C, Badu-Apraku B, Tetteh AY, et al. (2019) Assessment of genetic diversity for drought, heat and combined drought and heat stress tolerance in early maturing maize landraces. *Plants* 8: 518. https://doi.org/10.3390/plants8110518
31. Arslan A, Cavatassi R, Alfani F, et al. (2018) Diversification under climate variability as part of a CSA strategy in Rural Zambia. *J Dev Stud* 54: 457–480. https://doi.org/10.1080/00220388.2017.1293813
32. Fraval S, Hammond J, Bogard JR, et al. (2019) Food access deficiencies in Sub-saharan Africa: prevalence and implications for agricultural interventions. *Front Sustain Food Syst* 3: 104. https://doi.org/10.3389/fsufs.2019.00104
33. Joshi BK, Vista SP, Gurung SB, et al. (2020) Cultivar mixture for minimizing risk in farming and conserving agrobiodiversity. In: Gauchan D, Joshi BK, Bhandari B, et al. (Eds.), *Traditional Crop Biodiversity for Mountain Food and Nutrition Security in Nepal,* NAGRC, LI-BIRD, and Alliance of Bioversity International and CIAT, 14–25. Available from: https://himalayancrops.org/wp-content/uploads/2020/06/Traditional-Crop-Biodiversity-for-Mountain-Food-and-Nutrition-Security-in-Nepal.pdf.

34. Lal B, Gautam P, Panda BB, et al. (2017) Crop and varietal diversification of rainfed rice based cropping systems for higher productivity and profitability in Eastern India. *PLoS One* 12: e0175709. https://doi.org/10.1371/journal.pone.0175709
35. Nankya R, Mulumba J, Caracciolo F, et al. (2017) Yield perceptions, determinants and adoption impact of on farm varietal mixtures for common bean and banana in Uganda. *Sustainability* 9: 1321. https://doi.org/10.3390/su9081321
36. Tamburini G, Bommarco R, Wanger TC, et al. (2020) Agricultural diversification promotes multiple ecosystem services without compromising yield. *Sci Adv* 6: eaba1715. https://doi.org/10.1126/SCIADV.ABA1715
37. Attwood S, Estrada Carmona N, DeClerck F, et al. (2017) Using biodiversity to provide multiple services in sustainable farming systems. In: *Bioversity International, Mainstreaming Agrobiodiversity in Sustainable Food Systems: Scientific Foundations for an Agrobiodiversity Index,* Rome: Bioversity International, 53–80. Available from: https://hdl.handle.net/10568/89049.
38. Gaudin ACM, Tolhurst TN, Ker AP, et al. (2015) Increasing crop diversity mitigates weather variations and improves yield stability. *PLoS One* 10: e0113261. https://doi.org/10.1371/journal.pone.0113261
39. Raseduzzaman M, Jensen ES (2017) Does intercropping enhance yield stability in arable crop production? A meta-analysis. *Eur J Agron* 91: 25–33. https://doi.org/10.1016/j.eja.2017.09.009
40. Islam MS, Jahan H, Ema NS, et al. (2024) Determinants of crop diversification and its impact on farmers' income: A case study in Rangpur District, Bangladesh. *JSFA Rep* 4: 352–361. https://doi.org/10.1002/jsf2.216
41. Michler JD, Josephson AL (2017) To Specialize or Diversify: Agricultural Diversity and Poverty Dynamics in Ethiopia. *World Dev* 89: 214–226. https://doi.org/10.1016/j.worlddev.2016.08.011
42. Mango N, Makate C, Mapemba L, et al. (2018) The role of crop diversification in improving household food security in central Malawi. *Agric Food Secur* 7: 7. https://doi.org/10.1186/s40066-018-0160-x
43. Makate C, Wang R, Makate M, et al. (2016) Crop diversification and livelihoods of smallholder farmers in Zimbabwe: Adaptive management for environmental change. *Springerplus* 5: 1135. https://doi.org/10.1186/s40064-016-2802-4
44. Ochieng J, Kirimi L, Ochieng DO, et al. (2020) Managing climate risk through crop diversification in rural Kenya. *Clim Change* 162: 1107–1125. https://doi.org/10.1007/s10584-020-02727-0
45. Waha K, van Wijk MT, Fritz S, et al. (2018) Agricultural diversification as an important strategy for achieving food security in Africa. *Glob Chang Biol* 24: 3390–3400. https://doi.org/10.1111/gcb.14158
46. Feliciano D (2019) A review on the contribution of crop diversification to Sustainable Development Goal 1 'No poverty' in different world regions. *Sustain Dev* 27: 795–808. https://doi.org/10.1002/sd.1923
47. Danso-Abbeam G (2025) Crop diversification and multidimensional poverty in rural Ghana: the empirical linkages. *Sustain Futur* 10: 101122. https://doi.org/10.1016/j.sftr.2025.101122
48. Danso-Abbeam G, Amin KM, Ogundeji AA (2023) Enhancing Household Welfare through Perennial Crop Production in Northern Ghana. *Sustainability* 15: 451. https://doi.org/10.3390/su15010451

49. Meldrum G, Sidibe A, Padulosì S (2020) Promoting Bambara groundnut, fonio, and native vegetables for resilience and nutrition in Mali. Rome: Alliance of Bioversity International and CIAT. Available from: https://hdl.handle.net/10568/109362.
50. Rampa F, Knaepen H (2019) Sustainable food systems through diversification and indigenous vegetables: An analysis of the southern Nakuru County. SASS Report 1. Maastricht: ECDPM. Available from: https://ecdpm.org/work/sustainable-food-systems-through-diversification-and-indigenous-vegetables-an-analysis-of-the-southern-nakuru-county.
51. Ng'ang'a SK, Van Wijk MT, Rufino MC, et al. (2016) Adaptation of agriculture to climate change in semi-arid Borena, Ethiopia. *Reg Environ Chang* 16: 2317–2330. https://doi.org/10.1007/s10113-016-0940-4
52. Duong TT, Brewer T, Luck J, et al. (2019) A global review of farmers' perceptions of agricultural risks and risk management strategies. *Agriculture* 9: 10. https://doi.org/10.3390/agriculture9010010
53. Wegenast T, Hänze N, Haer R, et al. (2024) The effect of traditional agricultural practices on the food consumption of households facing extreme weather events in Tanzania. *Agric Food Secur* 13: 56. https://doi.org/10.1186/s40066-024-00512-1
54. Garbole J, Dima G, Kanchora D (2025) Livelihood diversification strategies and its impact on pastoral food security in Dubluk district, Borana zone, Southern Ethiopia. *Environ Sustain Indic* 28: 100894. https://doi.org/10.1016/j.indic.2025.100894
55. Dwivedi SL, Lammerts van Bueren ET, Ceccarelli S, et al. (2017) Diversifying food systems in the pursuit of sustainable food production and healthy diets. *Trends Plant Sci* 22: 842–856. https://doi.org/10.1016/j.tplants.2017.06.011
56. De Pinto A, Islam MM, Katic P (2023) Food security under a changing climate: Exploring the integration of resilience in research and practice. In: Béné C, Devereux S (Eds.), *Resilience and Food Security in a Food Systems Context,* Cham: Palgrave Macmillan, 207–237. https://doi.org/10.1007/978-3-031-23535-1_7
57. Onyeneke RU, Nwajiuba CA, Emenekwe CC, et al. (2019) Climate change adaptation in Nigerian agricultural sector: A systematic review and resilience check of adaptation measures. *AIMS Agric Food* 4: 967–1006. https://doi.org/10.3934/agrfood.2019.4.967
58. Meldrum G, Mijatović D, Rojas W, et al. (2018) Climate change and crop diversity: Farmers' perceptions and adaptation on the Bolivian Altiplano. *Environ Dev Sustain* 20: 703–730. https://doi.org/10.1007/s10668-016-9906-4
59. Hotz C, Loechl C, de Brauw A, et al. (2012) A large-scale intervention to introduce orange sweet potato in rural Mozambique increases vitamin A intakes among children and women. *Br J Nutr* 108: 163–176. https://doi.org/10.1017/S0007114511005174
60. Mabhaudhi T, Chimonyo VGP, Hlahla S, et al. (2019) Prospects of orphan crops in climate change. *Planta* 250: 695–708. https://doi.org/10.1007/s00425-019-03129-y
61. de Boef WS, Subedi A, Peroni N, et al., Eds. (2013) Community Biodiversity Management: Promoting Resilience and the Conservation of Plant Genetic Resources, Abingdon: Routledge.
62. Dapilah F, Nielsen JØ, Friis C (2020) The role of social networks in building adaptive capacity and resilience to climate change: a case study from northern Ghana. *Clim Dev* 12: 42–56. https://doi.org/10.1080/17565529.2019.1596063
63. Frison EA, Cherfas J, Hodgkin T (2011) Agricultural biodiversity is essential for a sustainable improvement in food and nutrition security. *Sustainability* 3: 238–253. https://doi.org/10.3390/su3010238

64. De Pinto A, Seymour G, Bryan E, et al. (2020) Women's empowerment and farmland allocations in Bangladesh: evidence of a possible pathway to crop diversification. *Clim Change* 163: 1025–1043. https://doi.org/10.1007/s10584-020-02925-w
65. Reynolds TW, Tobin D, Otieno G, et al. (2020) Differences in crop selection, resource constraints, and crop use values among female- and male-headed smallholder households in Kenya, Tanzania, and Uganda. *J Agric Food Syst Community Dev* 9: 65–92. https://doi.org/10.5304/jafscd.2020.094.011
66. Hansen JW, Vaughan C, Kagabo DM, et al. (2019) Climate services can support African farmers' context-specific adaptation needs at scale. *Front Sustain Food Syst* 3: 21. https://doi.org/10.3389/fsufs.2019.00021
67. Ragasa C, Lambrecht I, Mahrt K, et al. (2021) Can nutrition education mitigate the impacts of COVID-19 on dietary quality? Cluster-randomised controlled trial evidence in Myanmar's Central Dry Zone. *Matern Child Nutr* 17: e13259. https://doi.org/10.1111/mcn.13259
68. Amoak D, Najjar D (2026) Governing agrifood systems for climate resilience and gender inclusivity: A strategic review of the evidence. *Environ Dev* 57: 101308. https://doi.org/10.1016/j.envdev.2025.101308
69. Rubiyanto CW, Susanti W (2024) A current situation of agricultural practices: A report on cultivation methods from an isolated village in Javaa's Karst Mountains. *E3S Web Conf* 595: 03015. https://doi.org/10.1051/e3sconf/202459503015
70. Burchfield EK, Tozier de la Poterie A (2018) Determinants of crop diversification in rice-dominated Sri Lankan agricultural systems. *J Rural Stud* 61: 206–215. https://doi.org/10.1016/j.jrurstud.2018.05.010
71. McGuire S, Sperling L (2013) Making seed systems more resilient to stress. *Glob Environ Chang* 23: 644–653. https://doi.org/10.1016/j.gloenvcha.2013.02.001
72. Danso-Abbeam G, Ehiakpor DS, Aidoo R (2018) Agricultural extension and its effects on farm productivity and income: Insight from Northern Ghana. *Agric Food Secur* 7: 74. https://doi.org/10.1186/s40066-018-0225-x
73. Di Falco S, Bezabih M, Yesuf M (2010) Seeds for livelihood: Crop biodiversity and food production in Ethiopia. *Ecol Econ* 69: 1695–1702. https://doi.org/10.1016/j.ecolecon.2010.03.024
74. IPBES (2019) Summary for Policymakers of the Global Assessment Report on Biodiversity and Ecosystem Services. Bonn: IPBES Secretariat. Available from: https://www.ipbes.net/sites/default/files/ipbes_global_assessment_report_summary_for_policymakers.pdf.
75. Rohne Till E, Andersson M, Tsakok I (2024) *Political Leadership and Agricultural Transformation: A New Research Agenda,* Cham: Palgrave Macmillan. https://doi.org/10.1007/978-3-031-69852-1
76. Panda J, Parashari GS (2024) Empirical evaluation of agricultural resilience to climate change: an application to the Indian state of Odisha. *Theor Appl Climatol* 155: 8681–8702. https://doi.org/10.1007/s00704-024-05154-8
77. Das U, Ghosh S, Mondal B (2020) Resilience of agriculture in a climatically vulnerable state of India. *Theor Appl Climatol* 139: 1513–1529. https://doi.org/10.1007/s00704-019-03061-x
78. van Zonneveld M, Turmel MS, Hellin J (2020) Decision-Making to Diversify Farm Systems for Climate Change Adaptation. *Front Sustain Food Syst* 4: 32. https://doi.org/10.3389/fsufs.2020.00032

79. Wichern J, Descheemaeker K, Giller KE, et al. (2019) Vulnerability and adaptation options to climate change for rural livelihoods—A country-wide analysis for Uganda. *Agric Syst* 176: 102663. https://doi.org/10.1016/j.agsy.2019.102663
80. Altieri MA, Nicholls CI, Henao A, et al. (2015) Agroecology and the design of climate change-resilient farming systems. *Agron Sustain Dev* 35: 869–890. https://doi.org/10.1007/s13593-015-0285-2
81. Njeru EM (2013) Crop diversification: a potential strategy to mitigate food insecurity by smallholders in sub-Saharan Africa. *J Agric Food Syst Community Dev* 3: 63–69. https://doi.org/10.5304/jafscd.2013.034.006



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