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Livelihood adaptation to climate-related changes in agroecological zones in developing countries—challenges, prospects, and policy concerns

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Climate change significantly threatens the livelihoods, biodiversity, and food security within agroecological zones (AEZs) of developing countries. This research presents a systematic review of peer-reviewed articles published between 2013 and 2023, highlighting facilitators and deterrents of effective livelihood adaptation strategies across AEZs within developing nations. The study identified two main thematic areas from these studies across several geographic regions: Challenges and Policies. These thematic areas were common across the AEZs, each with four primary subthematic areas. These subthemes highlighted insufficient stakeholder engagement, inconsistent policies, environmental harm or damage, and technological deficiencies. The review highlights the urgency of incorporating traditional participatory approaches and enhancing stakeholder harmonisation for robust policy formation. It emphasises the need for a tailored approach to adaptation strategies to address the distinct social, ecological, and governance structures of each unique AEZ according to its geographic characteristics. Finally, this review offers a new perspective on the complexity of climate change adaptation in AEZs, while establishing the foundation for future scholarly work and policy initiatives pertinent to enhancing resilience and coping mechanisms to climate change within AEZs of developing nations.

KEYWORDS

agriculture, coping mechanisms, climate change, global warming, human activities

1 Introduction

Agroecological zones (AEZs) are distinct regions of land characterised by a unique combination of uniform agro-climate, ecology, soil types and agricultural practices [Food and Agriculture Organization of the United Nations (FAO), 1978]. AEZs have a critical role in food security in developing countries, where most of the population relies on smallholder farming and agriculture for their livelihood (Hossain et al., 2019). In recent decades, increased global temperatures and unstable climate conditions have amplified human-induced climatic impacts, affecting agricultural output and ecological balance (Abbass, 2023; Monaco, 2023). This has led to numerous uncertainties in the status quo and the management and adaptation of agroecological zones (AEZs) (Aniah et al., 2019). The resultant effects in AEZs are heightened frequencies of extreme floods, droughts, and wildfires, variability in rainfall and temperature patterns, and threats to food systems and ecological sustainability (Mutunga, 2023). Developing countries are especially susceptible due to their low levels of technical capacity, fragile institutions, and resource scarcity (Umemiya et al., 2021).

In Pakistan, for example, temperatures are expected to rise, and rainfall variability will likely increase by 2050, leading to more flooding, droughts and heat stress events (Savelli et al., 2022). Recent studies have shown an almost one-third inconsistency in crop yield due to rising global temperatures, resulting in climatic variations or increased variability in rainfall and temperature patterns (Zvobgo et al., 2023). This means that if the climate becomes more variable, agricultural production and food security can be compromised (Aggarwal et al., 2018). Apart from the adverse impacts on food security, damages sustained by AEZs (an example in Bangladesh) due to extreme weather and climatic events have led to population displacement, loss of livelihoods and threats to biodiversity and ecological niches, which are needed to ensure a balanced AEZ (Jayawardhan, 2017). Adaptation measures are thus acutely necessary for livelihood security and sustainable development. The strategies are constantly obstructed by fractured policy frameworks, poor stakeholder participation, and local variability in AEZs (Dube et al., 2016; Seaman et al., 2014).

These issues have been acknowledged by the United Nations Framework Convention on Climate Change (UNFCCC) since 1994, which has recommended that developing countries receive the highest priority in receiving financial incentives for livelihood adaptation (Eriksen et al., 2021). Rural economies within developing countries, specifically those in Latin America, Asia, Africa and the Caribbean, have recently endured economic hardships due to the loss of livelihood stemming from disruptions in AEZs by climate change (Madzivhandila and Niyimbanira, 2020; Tiyo et al., 2015). According to Hoque et al. (2019), approximately 2.5 billion people in developing countries depend on AEZs for income and survival; thus, comprehending vulnerability and adopting robust adaptation strategies are essential. A Tey et al. (2017) review concluded that developing countries struggle to adopt and implement sustainable agricultural practices.

Despite the increasing volume of literature on climate change adaptation, several gaps have persisted. These include a shortage of region-focused policy analysis, a limited emphasis on participation in governance processes, and a shortage of Latin American and Caribbean AEZ representation. Further, a shortage of systematic thematic syntheses complicates policymakers' and practitioners' navigation through the landscape of adaptation.

This paper fills these gaps by systematically reviewing how policy interacts with challenges and livelihood adaptive strategies in AEZs. It provides a thematic analysis with a clear structure, classifying literature into logical sub-themes to improve the practical utility of findings. The purpose of this review is to: (i) consolidate adaptation issues and policy measures in AEZs in developing countries; (ii) derive regionally based shifts in adaptation strategies; and (iii) put forward actionable recommendations for consideration in future adaptation planning. The research is aimed at policymakers, agricultural planners, NGOs, and academic researchers engaged in climate adaptation.

1.1 Literature review

Several studies have examined the socio-economic aspects of climate adaptation in AEZS. For example, according to the Ricardian approach, Hossain et al. (2019) analyse the economic effect of climate change on crop cultivation in Bangladesh. The results indicate important regional variations in vulnerability. In a different study, flood risk behavior in Bangladeshi smallholder farmers evidenced a low willingness to pay for insurance and indicated a necessity for non-monetary adaptation measures (Hossain, 2024, 2025).

The same concerns are reflected in the literature on efficiency and credit rationing in Boro rice cultivation (Rabbany et al., 2021), where it was discovered that access to resources considerably affects adaptive capacity. Taken in concert, these studies emphasise the necessity of interventions tailored to context and point to the inadequacy of one-size-fits-all approaches".

2 Materials and methods

This study was done using a systematic review process outlined and combined by Filyushkina et al. (2016), Pullin and Stewart (2006), and Snyder (2019). Existing peer-reviewed literature provides a solid foundation for any investigative or research endeavour looking for gaps and limitations, irrespective of the study area. A systematic review entails gathering and comparing findings, more often studying and evaluating effects to apprise policy and application or practices (Snyder, 2019). A systematic review is most appropriate and beneficial when analysing and extracting critical data and information across a large body of literature (Liberati et al., 2009).

This review examines livelihood adaptation measures within AEZs in developing countries, focusing on policy limitations that hinder successful adaptation to climate change. The principal aim is to highlight the socio-economic and demographic insights of farming communities, the effectiveness of adaptation strategies and the most commonly adopted methodologies found in the literature.

2.1 Search strategy

The primary data repositories used in this review were online scientific journal databases for peer-reviewed articles, including Google Scholar, EBSCOhost, Jstor, Lexis Library, vLex, and Research4life/HINARI. Grey Literature was obtained from the University of Guyana and social media platforms like LinkedIn, ResearchGate, and Academia.edu. Searches were limited to peer-reviewed publications from 2013 to 2023. Groundbreaking or prominent publications before 2013 were included for foundational context.

Search Terms and Strings were combined keywords such as:

"Agriculture Zones, Agroecological Zones" OR "AEZs".

"Livelihood adaptation" OR "Climate Change Adaptation".

"Low-income countries," "developing countries" OR "Underdeveloped nations".

Searches were refined using Boolean operators. Filters were configured to obtain the required publication type (peer-reviewed articles, government reports and NGO reports) and language (English).

2.2 The inclusion criteria and exclusion criteria

2.2.1 Inclusion criteria

Studies that alluded to or addressed adaptation measures within AEZs in developing countries.

Studies that evaluated the impacts of adaptation on agricultural productivity, environmental sustainability, and economic resilience within AEZs. Empirical studies consist of quantitative, qualitative, or mixed-method designs that focus exclusively on AEZs within developing countries. Research focused on policy-driven, technological, and/or community-based interventions within AEZs of developing countries.

2.2.2 Exclusion criteria

Studies were excluded if they focused on AEZs within developed countries. Studies that focused on non-AEZs. Studies that focus solely on mitigation strategies. Studies were solely based on theoretical models without empirical evidence or data. Opinionated pieces, columns, editorials, and studies lacking peer review or scrutiny from the scientific community were also excluded.

These strict criteria for inclusion and exclusion ensured that the review concentrated on actionable strategies compatible with the distinct challenges present in AEZs of developing countries.

2.3 Screening and selection process

The screening of articles was executed in three stages. The first stage was "Title Screening," followed by "Abstract" and "Full-Text Screening." One screener executed Title Screening, while two independent screeners were responsible for the second and third stages, "Abstract" and "Full-text Screening." Abstracts were reviewed to assess their relevance to the study. The evaluation of full-text articles was also executed based on the inclusion criteria.

Humans did the entire screening process—blinded fields, such as the authors' and journals' names, were applied during screening to reduce bias. A Kappa statistical test was used to measure the level of agreement between speakers (Nichols et al., 2010). A value between 0.61 and 0.8 indicates substantial agreement, while a value of 0.81 and above indicates perfect agreement. When discrepancies were highlighted, discussion and consensus were used to resolve these. Duplicate entries were removed using the reference management software EndNote. Decisions from each screening round were documented in XLSX and CSV formats using Microsoft Excel.

Figure 1 shows the PRISMA flowchart, summarising the identification, screening and selection of studies for inclusion in this systematic review (Page et al., 2021).

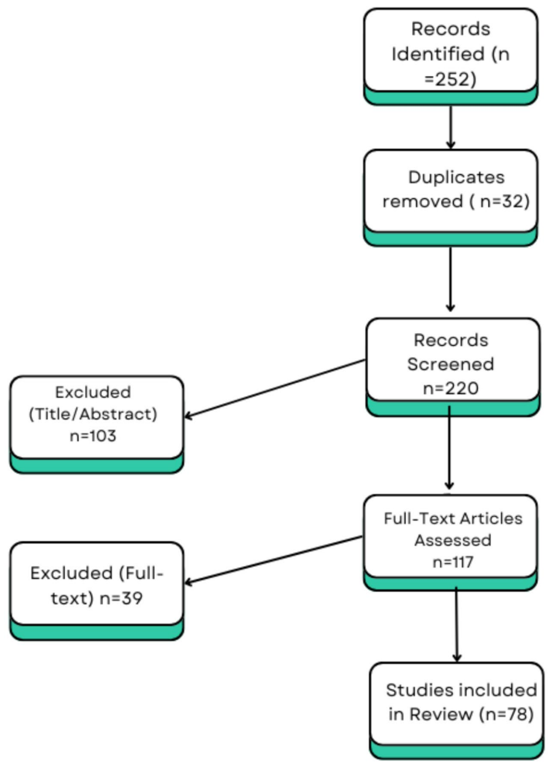

FIGURE 1
PRISMA-compliant flowchart outlining the selection process of articles in the review.

2.4 Quality assessment

Randomised and non-randomised studies evaluated the livelihood adaptation strategies in AEZs in developing countries. To reduce the risk of bias while ensuring methodological rigour, two tools were used:

1 The Cochrane Risk of Bias Tool (RoB 2.0), used with randomised controlled trials (RCTs) (Higgins et al., 2019)
2 ROBINS-1 [Risk of Bias Tool (RoB 2.0)] for non-randomised and observational studies (Sterne et al., 2016)

2.4.1 Application of the Cochrane risk of bias tool (RoB 2.0)

RCT used in this review evaluated interventions such as the impact of financial subsidies or policy interventions on agricultural productivity, testing the efficiency of irrigation systems and the introduction of crop-resilient varieties. The domains assessed were: (1) Randomisation (communities and farmers), ensuring these were randomly assigned to control groups and interventions. (2) Verification of Intended interventions (whether interventions were delivered and received as planned, and if deviations were documented correctly). (3) Measurement of Data from Outcome (Assessed whether results, e.g., crop yield, were consistently measured objectively across all participants). (4) Missing Data from Outcome (verification if missing data was handled appropriately, if outcomes were not reported from all participants). (5) Reported results (verified if all or selective outcomes were reported).

Each independent reviewer categorised studies as (a) having a low risk of bias, (b) having moderate concerns, or (c) having a high risk of bias. Any discrepancy was resolved through consensus among the moderators or arbitration involving a senior reviewer.

2.4.2 Application of ROBINS-1 (risk of bias tool (RoB 2.0) for non-randomised studies)

Most studies in the review focused on non-randomised real-world scenarios, e.g., assessing the impacts of changing climate patterns on livelihoods and comparing adaptation strategies across different geographical localities or farming communities. The domains assessed were: (1) Confounding Bias (assessed whether studies controlled for parameters such as disposable income, education level or farm size that can potentially influence results). (2) Selection of participants (evaluated whether farmers or communities were self-identified and selected or systematically distinct amongst comparison groups or interventions). (3) Classification of interventions (verified if interventions were consistently applied and clearly defined). (4) Deviations from intended interventions, (5) Missing data, (6) Quantification or Measurement of Outcomes and finally, (7) Bias in the selections of the results reported.

The two independent reviewers categorised studies into the following categories of bias: (a) low, (b) moderate, (c) serious or (d) critical.

Studies with critical ratings were excluded unless a sensitivity test showed that such inclusions would not significantly skew the overall review's results.

2.5 Sensitivity analysis

The exclusion of High-risk or Critical-risk studies from the Cochrane Risk of Bias Tool (RoB 2.0) and ROBINS-1 assessments was validated via a sensitivity analysis. These studies were reintroduced in the synthesis process to evaluate their impact on the findings and conclusions. If consistency was observed, then the exclusion of these studies was justified.

2.6 Synthesis of data

2.6.1 Data extraction

The qualitative and quantitative variables were extracted during the data synthesis process.

2.6.1.1 Data extraction

The primary dependent variables extracted from studies were economic impacts, agricultural yield/production, and effects on the environment and the farming community. Descriptive statistics, including sample sizes, standard deviations, means and variances, were all accounted for.

2.6.2 Data synthesis

2.6.2.1 Synthesis blinding

This technique minimised bias. Two independent synthesists worked on the data synthesis. The authors' identities and other study features were concealed to ensure that all conclusions were data-driven.

2.6.2.2 Qualitative synthesis

This was achieved via thematic analysis. Emerging and recurring themes about adaptation strategies were identified and categorised. The synthesis of these themes achieved a comprehensive understanding of adaptation measures and their effectiveness.

2.6.2.3 Quantitative synthesis

Where applicable, statistical aggregation methods were used to synthesise quantitative data, allowing for understanding the impacts of adaptation strategies adopted across studies.

2.6.2.4 Reconciliation process

The independent syntheses were reconciled via coordinated dialogue and discussions. In the event of a disagreement, a senior reviewer was then consulted as a mediator to attain balance and accuracy in the synthesis phase.

2.7 Reproducibility

A systematic protocol was first developed and registered with the OSF Registries (Doi: 10.17605/OSF.IO/DAX56), Centre for Open Science, to ensure transparency and rigour of the methodology used in this review.

2.8 Limitation

The following limitations of this review include:

1. The exclusion of studies that were not available in English, which could potentially introduce a language bias in the review
2. The inconsistency in the quality of grey literature
3. The limited availability of quantitative data affected the statistical synthesis.

3 Results and discussion

The synthesis uncovered two global themes—Challenges and Policies—each with four main sub-themes presented in Figure 2 and explained in full detail in what follows. The themes were found in 78 studies reviewed across varied AEZs in Africa, Asia, Latin America, and the Caribbean.

After synthesising the peer-reviewed literature, two main thematic areas emerged: challenges and policies. These principal themes were central to addressing adaptation uncertainties within AEZs. According to Lourenço et al. (2014), adaptation uncertainties refer to the unpredictable nature of the effectiveness of adaptation measures adopted or implemented. These unpredictable outcomes pose significant risks to ecosystem sustainability and agricultural productivity (Luo et al., 2022). The challenges identified are directly a result of insufficient data, bureaucratic barriers and difficulties with implementing strategies. The policies cover innovative strategies and existing frameworks designed to amplify adaptation efforts. Minor cross-cutting themes are discussed in 3.1; while not embedded in Table 1, these are referenced to contextualise their part in addressing adaptation uncertainties.

The literature highlighted four (4) key areas where challenges presented themselves in livelihood adaptation in AEZs and four (4) principal policy concerns across all levels and categories of stakeholders, as seen in Figure 2. These challenges and policies varied according to the locality or geography of the AEZ studied. These

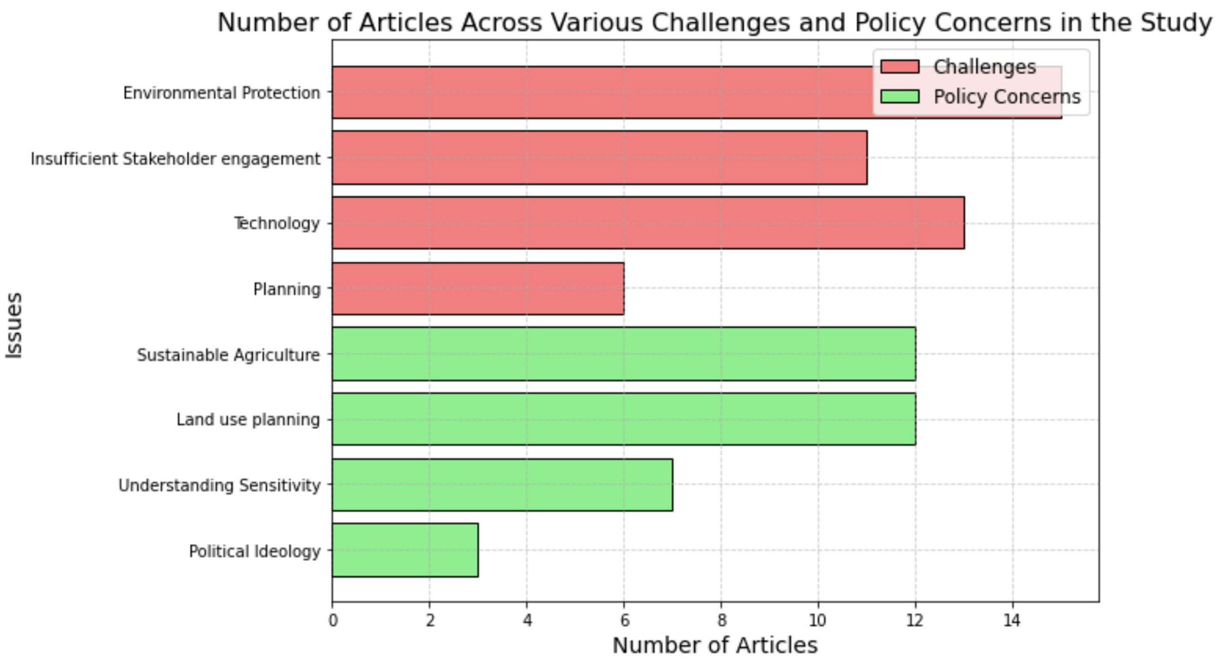

FIGURE 2
Occurrence of themes and sub-factors in the synthesised literature.

variations emphasised the urgency for nuanced approaches in each respective zone.

Challenges within the context of this review entail variables that present themselves within AEZs that directly affect the livelihood, causing degrees of uncertainty related to livelihood adaptation unless recommendations are swiftly implemented. Policy within the context of this review investigates administrative or political directives that must be streamlined for the sustainability of livelihoods and AEZs. The four (4) categories of challenges are as follows: (1) Environmental protection, in the context of this review, discusses how monitoring, security and the enforcement of regulations are crucial in the management and sustainability of AEZs. (2) Insufficient stakeholder engagement—addresses information sharing, correspondences, outreaches, partnerships and engagement amongst all participants or investors in AEZs. (3) Technology—adopting modern technology in agriculture and associated practices is highly costly (Gaffney et al., 2019). In this review, the challenges inherent in adopting technology allude to any instrument, hardware, or software and any methodological practice that must be adhered to successfully implement the desired adaptation measure in AEZs. (4) Planning relates to the challenges faced in successfully implementing livelihood adaptation strategies.

The four categories of Policy identified within the synthesised literature were as follows: (1) Sustainable agricultural practices – these policies required an extension services structure to assist farmers in implementing sustainable farming practices that consider both farmland and ecological health in the AEZ. (2) Land use policies – these were measures which directly spoke to land degradation in AEZs and how the absence of these institutional mechanisms affected the livelihood of farmers within AEZs. (3) Understanding Sensitivity – These policies highlighted within the literature referred to comprehending and addressing vulnerability, class and inequality amongst farmers, and (4) Political ideology-this spoke directly to the government agenda and was characterised by the philosophy of the government, aimed at shaping the culture of the society. Sustainable agriculture and land use planning were the most frequent policy instruments reported in the literature, with 15.2% of the studies sourced. Meanwhile, 8.9% of the policies addressed the lack of understanding of sensitivity in AEZs and provided prudent recommendations to address these gaps. Political ideology was the least evident theme of policies in the literature used in this study, comprising 3.8% of the articles synthesised (see Figures 2, 3).

3.1 Environmental protection challenges

A study in China used GIS and statistical analysis to highlight the rapid increase of ecological pressure due to human activities in AEZs, thereby threatening sustainable development (Zhang M. et al., 2022; Zhang X. et al., 2022). The results of the aforementioned study highlighted that more work is needed to prioritise environmental protection while balancing economic growth with ecological security. The diversity within the ecosystem is rapidly decreasing; species are directly threatened due to rapid urbanisation. This decline in species diversity challenges livelihood adaptation due to a significant reduction in crucial ecosystem services that farmers largely depend on. Kossebe et al. (2022) conducted a similar study in Cameroon and reported similar results to those mentioned above. The native *Adansonia digitata* (Baobab) tree in Cameroon, known for its diverse applications, is endangered, which can negatively impact the current and future generations of farmers within the AEZs. Industries are also negatively impacting the environment. A study by Tabe-Ojong et al. (2022) shows such impacts of the oil palm sector on the AEZs through soil erosion and degradation. Suggestions to improve the oil palm

TABLE 1 Articles and identified areas used in the review.

Key area identified	Geography	Representative authors and years
Challenges in environmental protection	Africa	Derbile et al. (2022), Kossebe et al. (2022), and Tabe-Ojong et al. (2022)
Challenges in environmental protection	Asia	Chen A. et al. (2022), Chen Y. et al. (2022), Gao et al. (2022), Liu et al. (2022), Zhang et al. (2007), Niu et al. (2023), Peng et al. (2017), Song et al. (2020), Ullah et al. (2019), Wang et al. (2021), Yao et al. (2022), Zhang M. et al. (2022), and Zhang X. et al. (2022)
Insufficient stakeholder engagement	Africa	Aidoo et al. (2021), Aniah et al. (2019), Antwi-Agyei et al. (2021), Kephe et al. (2020), Mihiretu et al. (2021), Tanimonure and Naziri (2021), and Tannor et al. (2022)
Insufficient stakeholder engagement	Asia	Chatterjee et al. (2021)
Insufficient stakeholder engagement	General	Lescourret et al. (2015) and Warner et al. (2022)
Insufficient stakeholder engagement	Latin America And The Caribbean	Fay Buckland and Campbell (2021)
Challenges in technology	Africa	Aliku and Oshunsanya (2018), Ibidhi and Ben Salem (2018), Lozano-Jaramillo et al. (2019), Maina et al. (2020), Musiyiwa et al. (2017), Uwizeyimana et al. (2018), and Wobeng et al. (2020)
Challenges in technology	Asia	Akhtar et al. (2022), Dey et al. (2020), Gupta and Mishra (2019), Mohapatra et al. (2021), Nabati et al. (2020), and Tian et al. (2014)
Challenges in planning	Africa	Enfors (2013) and Mugi-Ngenga et al. (2021)
Challenges in planning	Asia	Bapatla et al. (2022), Hossain et al. (2019), Zhang et al. (2020), and Muhammad et al. (2023)
Policy: sustainable agriculture	Africa	Besser et al. (2021), Dendir and Simane (2021), Kadiri et al. (2021), Ketema et al. (2021), Leauthaud et al. (2013), Ngetich et al. (2022), Rutebuka et al. (2019), and Zeleke et al. (2023)
Policy: sustainable agriculture	Asia	Basak et al. (2021), Dong et al. (2022), and Wang et al. (2022)
Policy: sustainable agriculture	General	Mrunalini et al. (2022)
Policy: land use planning	Africa	Tanougong and Tchamba (2022), Berihun et al. (2019), Mulualem et al. (2021), and Seo (2014)
Policy: land use planning	Asia	Chen et al. (2019), Devendra and Thomas (2002), Jiang et al. (2020), Malhotra et al. (2021), and Yan et al. (2020)
Policy: land use planning	Latin America And The Caribbean	Valverde-Arias et al. (2019)
Policy: land use planning	Global	Di Vittorio et al. (2016)
Policy: understanding sensitivity	Africa	Bonny et al. (2019), Mekonnen et al. (2019), Owusu et al. (2021), and Taye (2021)
Policy: understanding sensitivity	Asia	Jiang and Xu (2022), Lian et al. (2020), and Pandey and Bardsley (2015)
Policy: political ideology	General	Zhang et al. (2021) and Dunlap (2023)
Policy: political ideology	Latin America And The Caribbean	Féliz and ElisaMelón (2022)

sector for smallholder farmers while protecting the environment require better-quality farm inputs and a robust legal framework to define and protect land rights within AEZs. Without this legal framework, farmers' livelihoods and adaptive capacity in these areas could face ruin as the global impacts of human-induced climate change continue to surge. Challenges related to comprehending drivers of vegetation degradation require cooperative programs at various levels that identify the key influencing factors. Studies by Peng et al. (2017), Song et al. (2020), and Zhang et al. (2007) all highlight the challenges of protecting grasslands and nomadic culture, both crucial for ecological safety and sustainable farming in AEZs in China. Derbile et al. (2022) researched indigenous fruit trees (IFTs) using a mixed-methods approach in Ghana, where it was found that these IFTs were highly susceptible to excess rainfall, as well as below-average rainfall, leading to droughts, decreasing production yields and affecting the livelihoods of rural households' women in particular. Risk assessments, integrated approaches and monitoring are all essential in reducing vulnerability and building resilience in AEZs. The challenges are in satisfying the pre-requirements mentioned. Many developing countries lack the resources and studies to fulfil these objectives adequately. A key recommendation from the aforementioned study was the promotion of Environmental Change Adaptation Planning (ECAP) to conserve and propagate IFTs. A study by Chen A. et al. (2022) and Chen Y. et al. (2022) conducted on the composition of soil elements using statistical analysis found that the distribution of soil properties varied along changing environments, similar to the previously mentioned case. Ecological restoration in fragile zones is focused primarily on sensitive areas and environmental protection. However, challenges such as risk assessment, monitoring and integrated approaches still emerged to a lesser degree, according to Wang et al. (2021). Yao et al. (2022) demonstrated that the stage Slacks-Based Measure (SBM) Data Envelopment Analysis (DEA) SBM-DEA method can assess the ecological security in the Songnen-Sanjiang region in Northeast China from 2006 to 2019. However, the

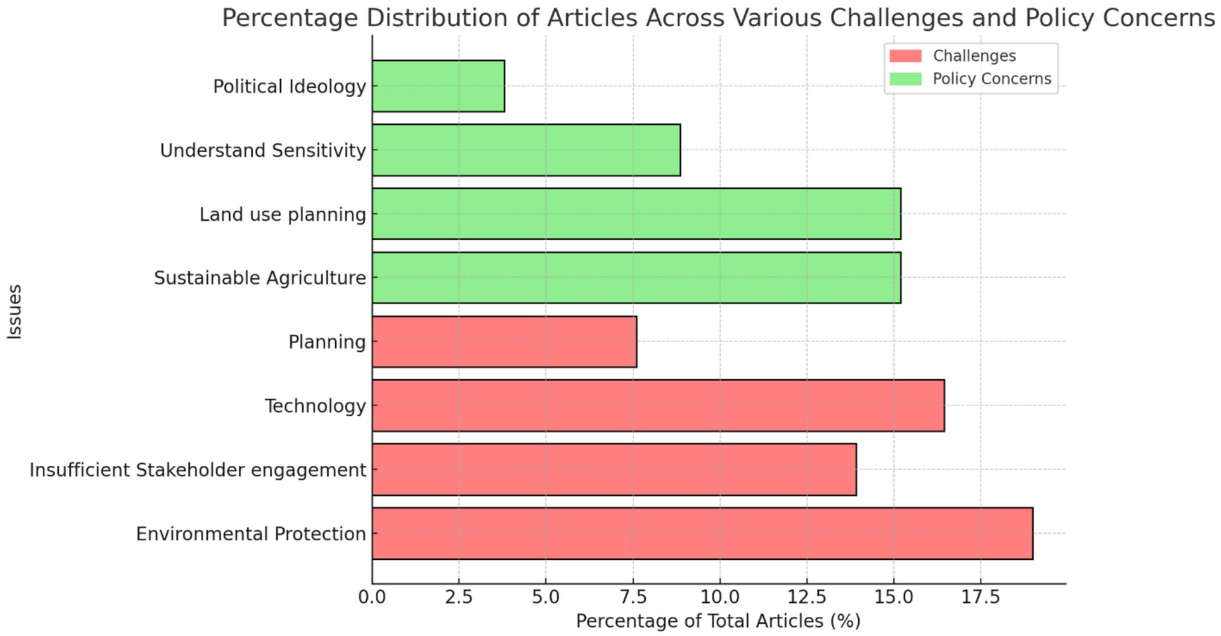

FIGURE 3
Percentage distribution of articles across issues highlighted.

certainty of these assessments depends on the accuracy of the model's input parameters. Without adequate ecological security, livelihoods face direct consequences; hence, the cautious interpretation of these results is emphasised.

Ecological security improved over time, and the Sanjiang Plains' environmental security was better than the Songnen Plain's. Again, in China, the important role of ecological engineering in promoting ecological restoration and the significant contribution of climate variability and change to net primary productivity (NPP) and soil retaining services were highlighted by Niu et al. (2023). The quality of the ecological data and the variability of the local environment determine the certainty of improvements in ecological security, contributions of ecological engineering and climate variability. This study helps address some of the challenges other regions face regarding ecological security. An increase in NPP would directly improve livelihoods, erosion prevention and nutrient and water retention, which are key factors that negatively impact AEZs. Another study by Gao et al. (2022) conducted in the karst area of Hechi, China, used a systematic approach to identify key ecological elements and prioritise areas for protection and restoration. However, the study alluded to the fact that as the socio-material needs of humans evolve, the uncertainty surrounding the benefits of projects geared towards environmental protection is becoming more evident. This presents a vivid challenge since livelihood adaptation would be more difficult to achieve. According to a study by Liu et al. (2022), sustainable agriculture and rural development can be achieved by harmonising energy development and ecological protection. This introduces a new paradigm, with challenges in developing environmentally friendly energy infrastructures in AEZs. Energy infrastructure impacts water resources via hydro plants and soil degradation via land use conversion. These challenges are comprehensive since agriculture relies on reliable energy to improve the efficacy in value-added processing, production and market access. Environmental protection is a prevalent challenge, but it is necessary to promote livelihood adaptation. As societies expand, more resources are consumed, increasing vulnerability and susceptibility. In Eurasia, Ullah et al. (2019) examined how human-natural systems have evolved in the Anthropocene, manipulating surface water and sediment dynamics to increase agricultural possibilities.

3.2 Challenges with stakeholder engagements

Communication, credibility, and knowledge awareness were hindrances to adopting climate services (Warner et al., 2022). The aforementioned study also highlighted inclusive and participatory approaches to stakeholder management as a transparent barrier to adopting sustainable practices through climate services. Kephe et al. (2020) also highlighted that climate change adaptation entails comprehending the present climatic conditions. Therefore, recommendations for better public-private partnerships and less bureaucracy to access financial aid must be prioritised. Mihiretu et al. (2021) looked at how Ethiopian agro-pastoral zone farmers perceived climate change and its origins, indicators, and impacts. The reasons, indicators, and impacts of climate change varied within different awareness groups. A lack of information and training was highlighted. A key recommendation was that better training and access to information can help farmers respond better to climate change. A Double Exposure Framework (adapted from Leichenko and O'Brien 2008) was used in rural Ghana to show that various factors, such as gender, occupation, location, and education, affect the perception of the effects on livelihoods. This study highlights a lack of farmer participation and empowerment among vulnerable groups. Tannor et al. (2022) concluded that the government and extractive industries should provide alternate sources of income and better infrastructure to increase adaptation in AEZs.

The government should promote the marketing of underutilised Indigenous vegetables (UIVs) and non-government entities in Nigeria, and relevant material on climate change should be made available to farmers. Adopting agroforestry and perennial plantations should be considered (Tanimonure and Naziri, 2021). The aforementioned study highlights the use of a fundamental mechanism. However, challenges and limitations are evident due to farmers' level of consciousness and insufficient information on climate change shared by the stakeholders responsible. Antwi-Agyei et al. (2021) suggested that climate information should be more directly relevant to farmers' needs to improve usability and accessibility. A qualitative study in Ghana revealed barriers to increasing its uptake, such as inadequate information, low accessibility, illiteracy, and difficulties understanding technical language. There is a need for an exchange of knowledge between smallholder farmers and structural or accredited institutions to guarantee the sustainability of local adaptation measures (Aniah et al., 2019). The previous study explores smallholder farmers' reactions to climate and environmental variation in two rural Savanna areas of Ghana. Again, in Ghana, a qualitative study revealed that farmers employed 17 adaptation strategies, with the most common being the modification of planting days, variation of crops, use of resistant species of crop, and the monitoring of weather predictions via radio by Aidoo et al. (2021) as a means of successfully implementing livelihood adaptation in AEZs.

Knowledge of farming, household size, and insights about the impact and severity of human-induced climate change were all factors that affected the method planning in farming practices and livelihood adaptation strategies. Chatterjee et al. (2021) concluded that conservation agriculture (CA) is seen as a means to ensure food security and biodiversity preservation. However, unless the awareness levels of all stakeholders are heightened, conservation agriculture cannot be successfully implemented, which threatens the long-term viability of farming systems. Younger, more educated farmers were likelier to use climate services (Fay Buckland and Campbell, 2021). The results provided in this previous study highlighted ways to improve the architecture and delivery of climate services to increase resilience amongst stakeholders. General research was done by Lescourret et al. (2015) using conceptual modelling, it is asserted that Ecosystem-based, ES-based management has the potential to ensure the sustainability of agricultural systems. However, challenges exist where new stakeholders must take the lead to coordinate management efforts, and practical instruments must be identified and constructed for use by these groups. We have seen via the synthesised literature that insufficient stakeholder engagement in AEZs has presented several challenges across developing countries. In Africa, limitations mainly referenced infrastructural limitations in communication (Aidoo et al., 2021). In Asia, cultural barriers were more predominant, as highlighted by Kephe et al. (2020).

3.3 Technological challenges in AEZs

The literature synthesis alluded to challenges in soil fertility management, access to appropriate tools and machinery, pest and disease management, irrigation and water management. If farmers do not adequately adopt prudent technology measures, livelihood adaptation strategies such as technology adoption, prudent water management, diversification of farming practices, and information and knowledge applications cannot be successfully implemented.

Musiyiwa et al. (2017) investigated how farmers obtained information and insights on soil and water management technologies in different AEZs in Zimbabwe. Using a qualitative approach, it was found that soil and water management techniques matched farmers' preferences. This implied that farmers who unsuccessfully adopted methods in implementing the appropriate irrigation systems and maintaining soil health and fertility saw less yield or output.

Aliku and Oshunsanya (2018) illustrated that the SOILWAT model accurately forecasted maximum water retention, soil compaction, permanent wilting point, and soil saturation. They recommended incorporating organic material, salinity and silt modification to improve the model outputs. Access to technology, such as the SOILWAT model, is critical for wise soil fertility management in AEZs, especially when considering the variability in soil types and fertility levels across AEZs. Dey et al. (2020) looked at the impact of burning agricultural waste on soil characteristics, biological characteristics, and crop production in two different AEZs of India and Bhutan. Results show that using crop remains as raw straw and biochar can increase farming outputs by 36 to 64%. However, the challenge in this adoption method entails providing the technical support necessary for farmers to adopt alternative crop residue management successfully. Farmers who implemented the aforementioned technique saw increased soil quality and crop yield. Understanding the soil profile of AEZs increases the likelihood of successfully implementing practices that promote more robust soil fertility management.

Challenges in low organic carbon stock AEZs affect soil fertility, nutrient cycling, water retention, infiltration and resilience to extreme events. Wobeng et al. (2020) showed that soybean cultivation strongly increased microbial biomass and carbon use efficiency in the Guinean savannah. These findings suggest that soybean cultivation soil can be a sustainable approach to enhance soil microbial effectiveness and nutrient cycling in low organic carbon stock areas to improve fertility and resilience. Similarly, Maina et al. (2020) highlighted the possible role of organic modifications using statistical analysis, specifically cow manure, in controlling plant parasitic nematodes in maise-bean harvesting schemes, which are economically important crops for food security in Kenya. Cover cropping in many AEZs, as described by the previously mentioned studies, most often requires appropriate technological solutions, such as access to precision agriculture tools for optimising planting and soil health monitoring systems. However, the successful adoption of these approaches is often obstructed by barriers such as insufficient financial resources, access to technology, a deficit in technical expertise amongst farmers and substandard infrastructure in rural areas.

Information and knowledge dissemination are crucial to farmers in AEZs, but challenges in applying predictive models can hinder the delivery of crucial information. For example, using GIS and distribution models, Lozano-Jaramillo et al. (2019) highlighted the challenges of predicting which livestock breeds are best suited for specific environments. This is difficult because of the dependency on climatic parameters. If these parameters are misconfigured due to a lack of data or incorrect parameterisation schemes, the model's efficacy is compromised, potentially resulting in suboptimal livestock losses. Mohapatra et al. (2021) used machine learning techniques to predict seasonal groundwater levels in India and found that the Deep Neural Network model is the most effective, with an accuracy of 72.22%. However, the prediction ability is poor in certain regions due to data availability, underscoring the need to strengthen groundwater monitoring networks and data acquisition systems. While predictive models hold great promise, their effectiveness is often restricted or limited by the availability and the quality of data, directly affecting their suitability for decision-making in AEZs. Akhtar et al. (2022) evaluated the Gravity Recovery and Climate Experiment (GRACE) to monitor changes in groundwater storage (GWS) in areas with limited groundwater monitoring systems. The correlation was poor in the mountainous region due to a delay of 4 months and limited observation wells. The complex terrain also caused inconsistencies in the connection due to variations in topography and subsurface characteristics. Therefore, caution should be exercised when interpreting GRACE's output in regions with varied geological and hydrological features since these factors influence groundwater assessments. These studies highlight challenges in data acquisition, which result in the underperformance of these technological applications designed to improve the sustainability of AEZs. Tian et al. (2014) proposed a joining outline among two extensively used crop simulations to enhance the micro foundation and effectiveness of the agroecological zone (AEZ) model. This framework consists of three steps: deriving, calibrating, and validating cultivar parameters, translating them into eco-physiological parameters, and applying the enhanced AEZ model. Another example by Gupta and Mishra (2019), a process-based crop simulation model was used to investigate the consequences of human-induced climate change on rice production in India by adopting AEZs instead of political boundaries.

According to the study, there is expected to be significant variability in different zones, and the changes in rice yield are expected to range from 2.9 to 17.8% in the 2080s. However, due to the geographical features of the study area, accurately calibrating the model was not without difficulties. The same hurdles can be faced if other AEZs with similar characteristics were to make use of this technology. Technology needs in AEZs vary significantly in terms of regions evaluated. Irrigation technologies and water usage were notably highlighted in arid regions, as also concretely suggested by Uwizeyimana et al. (2018). However, agricultural practices that build resilience to flooding are in demand in humid zones. Ibidhi and Ben Salem (2018) indicated that region-specific technological interventions must be considered to build the resilience of AEZs.

3.4 Planning and coordination challenges

Planning and coordination of activities in AEZs are interdependent due to increased climate variability. According to Muhammad et al. (2023), coordinating soil and climate conditions and planting challenges may negatively affect crop productivity. Hossain et al. (2019) and Zhang et al. (2020) forecasted that the impact varies by season and location as net crop revenues increase. Findings suggest that policymakers should consider specific AEZs when addressing the consequences of human-induced climatic change on crop agriculture. Seasonal variations pose challenges to farmers across different AEZs. Bapatla et al. (2022) highlighted the challenges of planning fertiliser applications by examining the impacts of surface air temperature on the Gram pod borer. This standard agricultural pest feeds on plants' protein biomolecules. Findings suggest that these predictions may help in planning and managing different zones of India, which promote adaptation and build resilience to temperature changes that are a consequence of human-induced climate change.

In Kenya, a study by Mugi-Ngenga et al. (2021) assessed how farmers use Indigenous knowledge in climatic prediction, their insights into climate variability, and adaptation plans. Challenges presented included integrating climate forecasting into farm planning activities. The study concluded that integrating Indigenous and conventional knowledge could be valuable for rain-fed-dependent smallholder farmers while planning for upcoming climatic seasons. Enfors (2013) investigated the ability of small-scale water system innovations (SWSIs) to increase productivity in farming systems. This type of transformation identified hurdles in planning and budgetary allocations available for integrating SWSIs in activities related to water resource management. The study concluded with recommendations for investment approaches to turn this potential into reality.

Without careful interventions in planning activities within AEZs across developing countries, the successful planning and execution of farming activities continue to be inhibited by challenges. Studies have shown that understanding climate variability is essential for developing robust agricultural strategies. Its relationship with crop yields and water availability is directly proportional (Challinor et al., 2014). Additionally, direct access to capital expenditure and financial resources is frequently highlighted as a key indicator of farming success in these zones (Kassie et al., 2015). Di Falco et al. (2011) observed that farmers with access to more capital were more likely to adopt climate-resilient strategies successfully. The aforementioned findings emphasise the need for targeted interventions supported by empirical evidence to improve livelihood adaptation in AEZs.

3.5 Policies for sustainable agriculture

The synthesised literature highlighted four principal policy concerns with varying applications across AEZs. The first policy highlighted in the literature is sustainable agricultural practices. Climate-smart agriculture has been identified as a key adaptation measure across AEZs. Mrunalini et al. (2022) highlight how legumes are highly suitable for climate-smart applications.

Besser et al. (2021) stated that restructuring farming systems to build resilience and adaptive capacity in AEZs emphasised the need for climate-smart agriculture and provided reasons why organisational and political efforts should be concerned about harmful environmental impacts from groundwater abstraction for agricultural purposes. Zeleke et al. (2023) have raised concerns about the effects on farmers' livelihoods and the sustainability of AEZs due to poor water quality from extracting deep, highly mineralised groundwater. Climate-resilient agricultural practices, if properly implemented, are necessary to decrease vulnerability. Similar studies related to climate-smart agriculture or climate-resilient practices highlighted concerns and the urgency to implement such policies related to water use and extraction done in Kenya by Malhotra et al. (2021). According to Wang et al. (2022) In Asia, soil erosion and its effects on farming are a concern, and a more integrated watershed management approach is needed. Population pressure was also found to result in stark contrasts between ecosystem service supply (ESS) and ecosystem social demands (ESD) of smallholder farmers, according to Ketema et al. (2021). Policies to address population growth, restore ESS, and improve SWB were all highlighted as practical measures in these AEZs. Ngetich et al. (2022)

also touched on the ESDs of smallholder farmers in Kenya since rainfed agriculture is vital in Kenya's arid and semi-arid zones. Enhancing livelihood adaptation can be achieved by combining scientific findings with local strategies to manage risks effectively in these AEZs.

Kadiri et al. (2021) studied the dynamics of Soil Organic Carbon (SOC) in arable land use in two AEZs in Nigeria. It was concluded that better soil management techniques improved SOC sequestration and soil fertility in the two AEZs, which can impact farmers' livelihoods. Climate and land use changes have weakened the interfaces among soil, plants, and grazing animals, reducing ecosystem services. Actions such as close-to-nature restoration and rotating grazing should be taken to recreate soil–plant–animal interfaces highlighted by Dong et al. (2022).

Dendir and Simane (2021) supported the implementation of all-inclusive policies concerning climate change adaptation strategies since variations in AEZs must be accounted for in order to implement livelihood adaptation successfully. Universally, the need for sustainable practices such as organic farming and crop rotation was recognised, but implementation can vary due to geography. In Asia, where drier regions are located, water harvesting and conservation are critical (Basak et al., 2021). Soil conservation, on the other hand, is a more pressing issue in Africa due to erosion caused by extreme climatic factors (Rutebuka et al., 2019).

3.6 Land use policies and their impact

Land allocation and zoning, restoration, conservation, ecosystem services, and infrastructure development are some of the few thematic areas highlighted across the literature synthesised. Tanougong and Tchamba (2022) demonstrated how climate change exacerbated the effects of forest cover loss via diversification, mainly for expanding AEZs, settlements, and livestock farming. Physical environments are critical in agriculture. Hence, farming practices vary widely based on these characteristics (Devendra and Thomas, 2002).

Land degradation results in losses and the inability to implement innovative adaptation measures against climate change's impacts, threatening farmers' sustainable livelihood. In some regions, ecological restoration projects are seen as a tangible solution to the issue of land degradation. Vegetation dynamics are highly related to climate change and its associated impacts on AEZs. Hence, understanding climate change projections is pivotal for successful land use policies. Di Vittorio et al. (2016) corroborate these findings by stating that results from projected future climate change data and historical climate data yielded different results. It was found that the uncertainty related to land demarcation should be measured. Therefore, biophysical and geopolitical factors are also important when modelling land change dynamics, as they provide the necessary evidence for appropriate land use policies.

These policies are very relevant as changes in land use patterns and livelihoods have significantly impacted traditional food systems in India. An example can be seen where the transition from traditional farming to commercial agriculture practices resulted in a decline in crop diversity and the migration of indigenous food sources. Malhotra et al. (2021) recommended reevaluating current tribal development practices in India, emphasising the need for more holistic socio-ecological approaches that integrate traditional knowledge and protect biodiversity while promoting agroecological farming. These approaches involve participatory land management that bolsters sustainable livelihoods, which align with the ecological and cultural needs of tribal populations. Yan et al. (2020) also examined the social and organisational changes in land use patterns and ecology, population relocation, land policy modifications, and social organisation reformations responsible for ecological degradation, affecting farmers' livelihoods. For example, Mulualem et al. (2021) demonstrate how various land uses and administration practices impact soil nutrient outflows in Ethiopia. Nutrient losses varied among AEZs, land use techniques and management practices, with cropland indicating the most losses compared to other types. However, management practices effectively reduced nutrient losses, mainly from water erosion. The variation of AEZs has been seen to show recurring concerns in how land use policies are crafted. Valverde-Arias et al. (2019) demonstrated significant differences in the environmental conditions between the two AEZs in Ecuador. These differences could impact the accuracy of Index-based Insurance (IBI). The IBI is a tool used primarily by smallholder farmers in developing countries to transfer risk. Essentially, it provides a degree of livelihood adaptation in these AEZs. Therefore, the land use policies cannot afford to neglect the key physical characteristics of AEZs, such as soil type, climatic features and topography. Governments should offer strategies and support to help farmers create a sustainable living landscape (Chen et al., 2019). The high-impact agricultural expansion was observed in forested areas in Asia by Jiang et al. (2020), Chen A. et al. (2022), and Chen Y. et al. (2022), which would require more robust frameworks. In Africa, however, according to Berihun et al. (2019) and Seo (2014), overuse of agricultural land is more prevalent, resulting in land degradation.

3.7 Understanding sensitivity in AEZs

A more profound comprehension of risk assessment and management allows policymakers to develop more appropriate strategies in AEZs (Thornton and Herrero, 2014; Gbetibouo and Ringler, 2009). Local development interventions should be based on the level of sensitivity according to Taye (2021), interventions should be based on the level of sensitivity. Climatic factors such as rainfall and temperature influence the differentiation of the populations (Bonny et al., 2019). Jiang and Xu (2022) studied how extreme climate affects vegetation in Northern China's Agro-pastoral Transition Zone. As in the prior study, temperature and precipitation mainly affected the Normalised Vegetative Index. The variation in hydrological variables and vegetation indices in AEZs is affected by rainfall (Lian et al., 2020).

Some AEZs may be more sensitive to two parameters: temperature and rainfall. This sensitivity to climate change and variability impacts crop yield, consequently affecting livelihoods. This implies the necessity for policymakers to take these concerns seriously. Vulnerable farming households are severely affected by AEZs. Mekonnen et al. (2019) also presented irrefutable evidence of the susceptibility of households and AEZs to climate change and environmental degradation. The adaptive capacity of households was the most significant factor influencing vulnerability, notably in the Ethiopian Highlands, and higher exposure in midland AEZs, for example, in central Ethiopia. The poorest households, commonly located in lowland areas, accompanied by low livelihood diversity, were identified as highly vulnerable.

A study in Nepal found that the region's social ecosystems are highly susceptible to climate change. Substantial exposure and sensitivity to extreme weather events also limit adaptive capacity (Pandey and Bardsley, 2015). A key recommendation is to adopt an adaptation policy that addresses the most vulnerable households before expanding the reduction of social ecosystems nationally. The susceptibility of AEZs is proportional to the degree of environmental stressors or disturbances they face. Economic support mechanisms must be the key policy directive of areas with high poverty rates. In contrast, innovation and dissemination of knowledge should be prioritised in more technologically advanced regions Owusu et al. (2021).

3.8 The role of political ideologies in adaptation

Governance structures, economic systems, and universal policies contribute to crafting adaptation strategies. Various policy approaches have been the subject of concern and criticism across the studies. Féliz and ElisaMelón (2022) found that capitalism has a significant role in today's human-induced global climate crisis due to its emphasis on free market exploration of resources. Similarly, communist ideology has caused a need for concern relating to environmental sustainability. Large-scale projects, such as the Belt and Road Initiative (BRI), according to Zhang et al. (2021), traverse areas with fragile ecosystems that are highly susceptible to the adverse effects of human-induced climate change. Agriculture trade, investment, and infrastructure development can impact livelihood adaptation in AEZs. However, there is a gap in the literature that alludes to the BRI's environmental impacts. More research is recommended so that the impacts and environmental changes due to the BRI can be better comprehended in BRI environments and ensure future sustainability in these regions.

The green economy framework is often touted as a more sustainable approach by Governments worldwide. Dunlap (2023) argues that the green economy prohibits cohesive self-reflection and actions to recover ecosystems and address systemic socio-ecological issues adequately. The aforementioned policies highlight the complexity of adaptation strategies, which, apart from political ideologies, are also heavily influenced by the broader political, environmental, and economic landscapes. The efficacy of adaptation policies varies between geographical regions. This effectiveness relies heavily on economic conditions, governance, and international cooperation and relations.

3.9 Final thoughts and synthesis of key themes

A notable gap is highlighted in the comprehensive assessment of region-specific adaptation strategies, which evaluates their long-term robustness. It is also noted that very few of these studies analyse the contextual factors that ultimately determine the success or failure of adaptation strategies. There is a need for a more granular analysis of how these measures can be tailored to local contexts, specifically where AEZs in developing countries differ in climatic conditions, ecology, and socio-economic conditions. Broad generalised solutions are primarily found in the body of literature synthesised, often neglecting the crucial role of key socio-economic indicators: cultural norms, the level of education, social capital, and financial readiness. These aforementioned factors directly affect the adaptability and sustainability of adaptive strategies.

Also, this study shows a need for longitudinal studies assessing the long-term impacts of adaptive measures, which question the integrity and sustainability of adaptation interventions over time. Unexplored factors, such as the intersection of climate change with other concerns, such as market volatility, land tenure insecurity, and political instability, remain largely unexplored in existing research. In regions of high vulnerability, where smallholder farming communities are located in Asia, Africa, Latin America, and the Caribbean, this gap is notably evident, where a scarcity of available resources suppresses the adaptive capacity of AEZs. Identifying and addressing these implications are pivotal in developing tailored, region-specific policies that account for the social, economic and diversified environments and enhancing the resilience of AEZs.

These thematic trends are consistent with South Asian and West African studies. Hossain et al. (2019), Basak et al. (2021), and Dube et al. (2016), for example, in Bangladesh and Sahel countries, reported the enduring barriers to stakeholder disconnection, insufficient financial channels, and technological deficits. These findings affirm the cross-region applicability of the problems and policy shortcomings outlined in this review but highlight context-specific adaptation strategy approaches.

4 Conclusion and recommendations

This systematic review of peer-reviewed literature explicitly focuses on livelihood adaptation strategies adopted by agroecological zones (AEZs) in developing countries. Two main thematic areas were identified that hinder the smooth and effective adoption of livelihood adaptation strategies to climate change within AEZs. Those two thematic areas were Challenges and Policies. Challenges included environmental protection, technology constraints, and insufficient stakeholder engagement and planning. Policies comprise Sustainable Agriculture, Land-use Planning, Understanding Sensitivity and Political Ideologies.

The consolidation and analysis of 78 studies within the review presents a novel framework that expounds the dynamics of constraints and enablers of livelihood adaptation. More importantly, it emphasises the urgency of tailoring these policies to the social, ecological, and governance frameworks of each unique AEZ, considering its geographical and cultural characteristics. Thereby migrating from a broad-brush or generic approach to implementing livelihood adaptation strategies.

5 Key contributions

A new classification of adaptation hindrances and policy gaps across AEZs

1. The stratified geographical analysis includes Africa, Asia, Latin America and the Caribbean Regions
2. The acknowledgement of how understudied themes, such as how political ideologies and stakeholder awareness work in implementing adaptation strategies.

6 Policy implications

- Adaptation strategies should integrate contemporary methods and traditional knowledge to increase farming communities' resilience.
- Participatory planning should be emphasised in policy formation, especially in areas with low adaptive capacity.
- Private-public partnerships and communication on climate services must be improved to bridge critical stakeholder gaps.

7 Recommendations

1 Environmental protection: the application of Environmental Change Adaptation Planning (ECAP) must be enhanced and complemented by ecosystem-based practices.
2 Stakeholder engagement: multi-level governance systems can promote collaboration, trust, and information sharing.
3 Technology adoption: farmers should be afforded access to predictive modelling tools, and the investment in data acquisition systems should be prioritised.
4 Planning: planning frameworks should incorporate indigenous knowledge systems.
5 Policy support: the implementation of region-specific policies regarding sustainable agriculture and land use, following the distinct sensitivities of AEZs
6 Governance reform: establish strong institutions to monitor the impacts of large-scale development and ensure that policies comply with green economic frameworks.

8 Future directions

Future studies should incorporate the following:

- Enhance the inclusion of marginalised regions like Latin America and the Caribbean
- Cross-cutting concerns should be thoroughly assessed, such as political instability and the insecurity of land tenures
- Strong methodologies should be established to evaluate the long-term impacts of adaptation strategies.

Author contributions

EH: Investigation, Software, Conceptualization, Writing – original draft, Resources, Funding acquisition, Writing – review & editing, Visualization, Data curation, Validation, Formal analysis, Methodology. TO: Project administration, Supervision, Validation, Methodology, Funding acquisition, Conceptualization, Investigation, Resources, Writing – review & editing. EC: Conceptualization, Visualization, Supervision, Writing – review & editing. SM: Conceptualization, Writing – review & editing, Investigation, Data curation.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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