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Geological and hydrometeorological hazards affecting livestock production in Ethiopia: a systematic review of impacts, mitigation, and adaptation strategies

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Introduction: Ethiopia's livestock sector is critically vulnerable to a wide range of geological and hydrometeorological hazards that undermine animal health, productivity, and the livelihoods of pastoral communities. The country's geographic location along the East African Rift System increases its susceptibility to geological threats such as volcanic eruptions, earthquakes, and landslides, while climate variability exacerbates hydrometeorological risks including droughts and floods.

Methods: This systematic review adheres to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines and employs a structured search strategy across major academic databases including Scopus, Web of Science, and Google Scholar. Studies were selected based on predefined inclusion and exclusion criteria to ensure the relevance and quality of the literature reviewed.

Results: The review synthesizes findings from high-quality studies to qualitatively assess the compound impacts of geological and hydrometeorological hazards on livestock production in Ethiopia, particularly within pastoral and agro-pastoral systems. Drought emerges as the most significant hazard, with more than 6.8 million livestock deaths reported since 2020 due to successive failed rainy seasons. Floods have also caused severe damage; for instance, the 2006 flooding in the Southern Nations, Nationalities, and Peoples' Region (SNNPR) resulted in the loss of approximately 15,600 livestock. In contrast, direct data on geological hazards such as volcanic eruptions and earthquakes remain limited, though their indirect effects—such as ashfall on grazing lands, water contamination, and disruption of grazing routes—further compromise livestock productivity and resilience.

Discussion: The review highlights critical gaps in data and research, particularly regarding the direct impacts of geological hazards. It identifies key adaptation and mitigation strategies, including early warning systems, hazard mapping, veterinary service enhancement, livestock diversification, and the promotion of livestock insurance schemes. Strengthening policy frameworks, community

engagement, and economic instruments is essential to build resilience in the livestock sector. Evidence-based interventions are urgently needed to safeguard livelihoods, ensure food security, and promote sustainable adaptation in Ethiopia's hazard-prone regions.

KEYWORDS

geologic hazards, livestock production, Ethiopia, mitigation strategies, adaptation measures

1 Introduction

Geological hazards including earthquakes, volcanic eruptions, landslides, and soil subsidence are among the most disruptive natural events, posing significant risks to ecosystems, human settlements, and economic stability worldwide (Lin et al., 2021). These hazards not only cause direct destruction but also trigger secondary effects, such as water contamination, land degradation, and increased susceptibility to disease outbreaks (Ayele et al., 2021). Ethiopia, situated within the geologically active East African Rift System, is highly susceptible to these hazards, with pastoralist and agro-pastoralist communities being particularly vulnerable due to their dependence on livestock-based livelihoods (Lemenkova, 2022). Livestock farming is a vital component of Ethiopia's economy, providing food, income, and employment for millions, yet it remains highly sensitive to environmental shocks (Asresie et al., 2015). The recurrent nature of geologic hazards significantly disrupts livestock production by damaging rangelands, reducing water availability, and displacing herding communities, all of which have cascading effects on livestock productivity, market access, and overall economic stability (Abaynew et al., 2024). In addition to geological hazards, Ethiopia experiences frequent hydrometeorological hazards such as droughts, floods, and extreme weather events further exacerbating the challenges faced by livestock farmers (Bachewe et al., 2018). The interplay between climate variability and geologic hazards compounds the stress on livestock systems, as climate-induced droughts increase soil instability, making landslides and erosion more frequent, while extreme rainfall events intensify soil subsidence and flooding risks (Bogale and Erena, 2022). These multi-hazard interactions create a complex web of threats that undermine livestock health, grazing dynamics, and the resilience of market systems (Solomon and Belete, 2019). However, despite the well-documented impacts of climate-induced hazards on Ethiopian agriculture, research focusing on the specific effects of geological and hydrometeorological hazards on livestock remains scarce.

Existing literature on Ethiopian geologic hazards has largely emphasized their environmental and infrastructural impacts, with limited attention given to the livestock sector. For instance, while Bogale and Erena (2022) explored the consequences of drought and land degradation on livestock, their study primarily centered on climate-induced stressors, failing to address the cumulative effects of geological hazards such as landslides and volcanic eruptions, which further reduce access to critical resources. Similarly, Tadesse et al. (2024) analyzed landslide impacts on agriculture and infrastructure but offered minimal discussion on how such events disrupt livestock production, displace herders, and heighten the risk of disease outbreaks due to constrained movement and resource depletion. Getu (2020) examined the socio-economic consequences of volcanic eruptions but only briefly mentioned their implications for livestock, despite the well-established risks of ashfall-induced respiratory illnesses, toxic contamination of water sources, and long-term degradation of grazing lands. More comprehensive assessments, such as Mebrahtu et al. (2020), provided insights into geological hazards in Ethiopia but did not integrate livestock-specific vulnerabilities, leaving a crucial gap in understanding the sector's exposure to these hazards.

Addressing this research gap, this systematic review seeks to provide a comprehensive analysis of the impact of geological and hydrometeorological hazards on livestock production in Ethiopia. Specifically, it aims to: (1) examine the major geological and hydrometeorological hazards affecting livestock production, (2) assess the economic and market implications of such hazards on Ethiopia's livestock sector, (3) analyze how climate change exacerbates these hazards and their compounded effects on livestock, and (4) evaluate existing adaptation and mitigation strategies for enhancing livestock resilience. By synthesizing diverse sources of research and case studies, this review will offer an evidence-based perspective on the multi-faceted challenges confronting livestock-dependent communities and identify strategies to enhance adaptive capacity and risk reduction efforts in the sector. To achieve these objectives, this systematic review adopts a structured approach, synthesizing peer-reviewed literature, government reports, and case studies on geological and hydrometeorological hazards affecting Ethiopian livestock production. The methodology involves a rigorous selection and evaluation of relevant studies to ensure a comprehensive understanding of hazard-livestock interactions, their socio-economic implications, and the effectiveness of adaptation and mitigation strategies. The following section outlines the research design, data sources, inclusion criteria, and analytical framework employed in this review.

1.1 Research questions

1. What are the major geological and hydrometeorological hazards affecting livestock production in Ethiopia?
2. How do these hazards impact livestock productivity, health, and market systems?
3. In what ways does climate change exacerbate geologic and hydrometeorological hazards in Ethiopia?
4. What adaptation and mitigation strategies have been implemented to enhance the resilience of Ethiopia's livestock sector, and how effective are they?

2 Methodology

This systematic review employs a rigorous, transparent, and replicable methodology to critically assess the impacts of geological and hydrometeorological hazards on livestock production in Ethiopia, as well as the adaptation and mitigation strategies employed to enhance livestock resilience. The review is conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines to ensure methodological rigor, reliability, and comprehensiveness. By synthesizing a broad range of scholarly and policy-oriented literature, the study aims to provide an evidence-based understanding of the intersection between geophysical hazards, climate variability, and livestock sustainability in Ethiopia. The methodological approach encompasses an extensive literature search, systematic selection of relevant studies, thematic data extraction, critical appraisal of sources, and an integrative synthesis of findings.

2.1 Literature search and data sources

The review begins with a comprehensive literature search targeting peer-reviewed journal articles, government reports, international agency publications, and credible gray literature. To ensure a robust and multidisciplinary approach, the search is conducted across multiple databases, including Scopus, Web of Science, ScienceDirect, Google Scholar, and specialized repositories from organizations such as the Food and Agriculture Organization (FAO) and the United Nations Environment Programme (UNEP). The search strategy employs Boolean operators to refine results and maximize the retrieval of relevant studies, incorporating keywords such as "geological hazards," "hydrometeorological hazards," "livestock production," "climate change impacts," "adaptation strategies," and "Ethiopia." To maintain both historical context and relevance, the review primarily focuses on studies published between 2000 and 2024, allowing for an assessment of long-term trends and emerging challenges in the Ethiopian livestock sector.

2.2 Inclusion and exclusion criteria

To ensure the inclusion of high-quality and thematically relevant studies, strict selection criteria are applied. Studies are eligible if they specifically analyze the effects of geological hazards such as earthquakes, landslides, and volcanic activity, as well as hydrometeorological hazards such as droughts, floods, and extreme temperature fluctuations on livestock productivity, health, and market systems in Ethiopia. Preference is given to empirical research presenting quantitative and qualitative data, particularly those incorporating longitudinal assessments of hazard impacts. Additionally, studies discussing the compounded effects of climate change on these hazards and the resilience of Ethiopia's livestock sector are prioritized. Publications that lack a clear methodological foundation, anecdotal reports, opinion pieces, or studies conducted outside the Ethiopian context without direct applicability are excluded to maintain scientific integrity and ensure a robust evidence base.

2.3 Data extraction and thematic synthesis

Following study selection, data extraction is carried out systematically using a structured framework to facilitate comparative analysis. Extracted data encompass key thematic dimensions, including the specific hazards affecting livestock, the nature and extent of their impacts on productivity, health, and market structures, and the role of climate change in amplifying these hazards. Furthermore, adaptation and mitigation strategies are assessed in terms of their effectiveness, economic feasibility, and institutional support mechanisms. Thematic synthesis is employed to integrate findings across studies, allowing for the identification of recurring patterns, regional disparities, and knowledge gaps in livestock hazard management in Ethiopia. Quantitative data, where available, are analyzed descriptively to reveal broader trends, while qualitative insights are synthesized to provide a nuanced understanding of localized responses to environmental stresses.

2.4 Quality assessment and bias minimization

To uphold the credibility and validity of the synthesized findings, a systematic quality appraisal process is conducted using established critical appraisal tools such as the Critical Appraisal Skills Programme (CASP) checklist and the Mixed Methods Appraisal Tool (MMAT). Studies are evaluated based on the clarity of their research objectives, the robustness of their study design, the adequacy of their data collection and analysis methods, and the relevance of their findings to Ethiopia's livestock sector. To minimize selection and interpretation bias, an independent cross-validation process is undertaken, wherein two reviewers assess each study's methodological rigor and resolve discrepancies through discussion and consensus. This rigorous appraisal ensures that only scientifically sound and contextually relevant studies inform the review's conclusions.

2.5 Limitations and mitigation measures

Despite the methodological robustness of this systematic review, certain limitations must be acknowledged. The exclusion of non-English publications may introduce a language bias, potentially omitting valuable studies that document region-specific experiences with livestock hazards in Ethiopia. Additionally, the significant heterogeneity observed across the reviewed studies, particularly in data collection techniques and impact assessment methodologies, may limit direct comparability and the feasibility of meta-analysis. Furthermore, the scarcity of long-term studies examining the sustained effects of geological and hydrometeorological hazards on livestock constrains the ability to draw definitive conclusions about long-term resilience-building efforts. To mitigate these limitations, sensitivity analyses are conducted where applicable, and findings are interpreted within the context of Ethiopia's diverse ecological and socio-economic landscapes to avoid overgeneralization.

2.6 Contribution and scope

By employing this rigorous methodological framework, the review aims to generate actionable insights that can inform policy interventions, enhance livestock adaptation strategies, and contribute to sustainable livestock management in Ethiopia. The findings serve as a foundation for evidence-based decision-making, offering a comprehensive synthesis of the complex interplay between geological and hydrometeorological hazards, climate change, and livestock sector resilience. The subsequent sections present the results of this systematic synthesis, detailing the key trends, challenges, and opportunities that emerge from the reviewed literature.

3 Results

This section presents a comprehensive analysis of the impacts of geological and hydrometeorological hazards on livestock production in Ethiopia. It begins with an overview of the existing literature, followed by an examination of the key hazards affecting the sector, such as earthquakes, volcanic eruptions, droughts, and floods. The section explores the various ways these hazards impact livestock productivity, health, and market systems, with particular emphasis on the vulnerability of livestock systems in different regions. Furthermore, it delves into the socio-economic and environmental consequences of these hazards, highlighting the broader implications for rural communities and ecosystems. The interactions between climate change and geological hazards are also discussed, as they exacerbate the challenges faced by livestock producers. Finally, the section reviews existing adaptation and mitigation strategies, assessing their effectiveness in building resilience and reducing the impacts of these hazards on Ethiopia's livestock sector.

3.1 Overview of included literature

A total of 300 records were identified through various search strategies. Specifically, 250 records were retrieved from multiple electronic databases, including Google Scholar (n = 77), PubMed (n = 55), Science Direct (n = 44), Web of Science (n = 39), and Scopus (n = 35). An additional 50 records were obtained from other sources, such as government reports and publications (n = 19), conference proceedings and seminars (n = 13), and grey literature (n = 18). Following the removal of duplicate records, 200 unique records remained. These were subjected to an initial screening based on title and abstract, resulting in the exclusion of 60 records that did not meet the inclusion criteria. Subsequently, 180 records underwent further evaluation, with 120 full-text articles assessed for eligibility. During the eligibility assessment, 15 articles were excluded for various reasons: three were published before 2005, seven lacked relevance to the study's main themes, two were not written in English, two contained insufficient data, and one presented a non-comparable context. Furthermore, 46 additional records were identified through expert consultation (n = 27) and reference checking (n = 19), bringing the total number of eligible records to 105. These records comprised 87 journal articles, 8 reports, 6 conference proceedings, and 4 grey literature sources, which were ultimately included in this review. This systematic approach ensured a comprehensive and methodologically rigorous selection of relevant literature for the study. Figure 1 illustrates the PRISMA flow diagram, detailing the selection process of the included studies. The diagram outlines the number of records identified, screened, excluded, and ultimately included in the review, ensuring transparency and reproducibility in the study selection methodology.

3.1.1 Thematic distribution of literature

A total of 105 sources were included in the review, of which 75 were used for thematic and meta-analysis. Figure 2 illustrates the distribution of studies across different climate-induced and geological hazards. Drought emerged as the most extensively studied hazard, with 17 studies (22.7%) analyzing its impacts on livestock production. The literature highlights significant reductions in pasture availability, water scarcity, and increased livestock mortality. Studies indicate that drought events have intensified over the past three decades, with projections suggesting further increases in frequency and severity. Floods accounted for 11 studies (14.7%) of the reviewed literature, primarily examining the impact of riverine and flash floods in lowland pastoral regions. The findings suggest that recurrent floods lead to widespread livestock displacement, loss of grazing land, and increased vulnerability to diseases. The literature also emphasizes the lack of effective flood mitigation strategies in Ethiopia's livestock sector. Soil erosion and degradation, along with landslides, were examined in 12 and 14 studies, respectively (16% and 18.7%). The focus was on highland areas where excessive land degradation reduces pasture productivity. The literature underscores that increased erosion rates, driven by erratic rainfall and land mismanagement, contribute to declining livestock carrying capacity. Landslides were noted as a localized but serious threat in steep-slope regions, often triggered by extreme rainfall and poor land-use practices. Volcanic hazards were addressed in nine studies (12%), primarily in areas near the Rift Valley. Findings suggest that volcanic eruptions lead to land degradation, soil toxicity, and loss of livestock due to ashfall and gas emissions. However, literature on long-term adaptation strategies to volcanic hazards remains scarce. Earthquake-related impacts on livestock were the least studied, with 12 studies (16%) focusing on this hazard. The reviewed literature indicates that while direct livestock mortality due to earthquakes is minimal, indirect effects such as structural damage to water sources, storage facilities, and grazing land disruption pose long-term challenges for pastoral communities. Despite the extensive research on drought and floods, significant knowledge gaps remain regarding the long-term adaptation strategies for geological hazards. Additionally, integrated studies analyzing the cumulative impacts of multiple hazards on livestock production are scarce. The review also highlights the limited availability of quantitative data on economic losses attributed to each hazard type. The findings indicate a research bias toward hydro-meteorological hazards, particularly drought and floods, while geological hazards receive comparatively less attention. Addressing these gaps through interdisciplinary research and policy-focused studies is essential for developing comprehensive mitigation and adaptation strategies for Ethiopia's livestock sector.

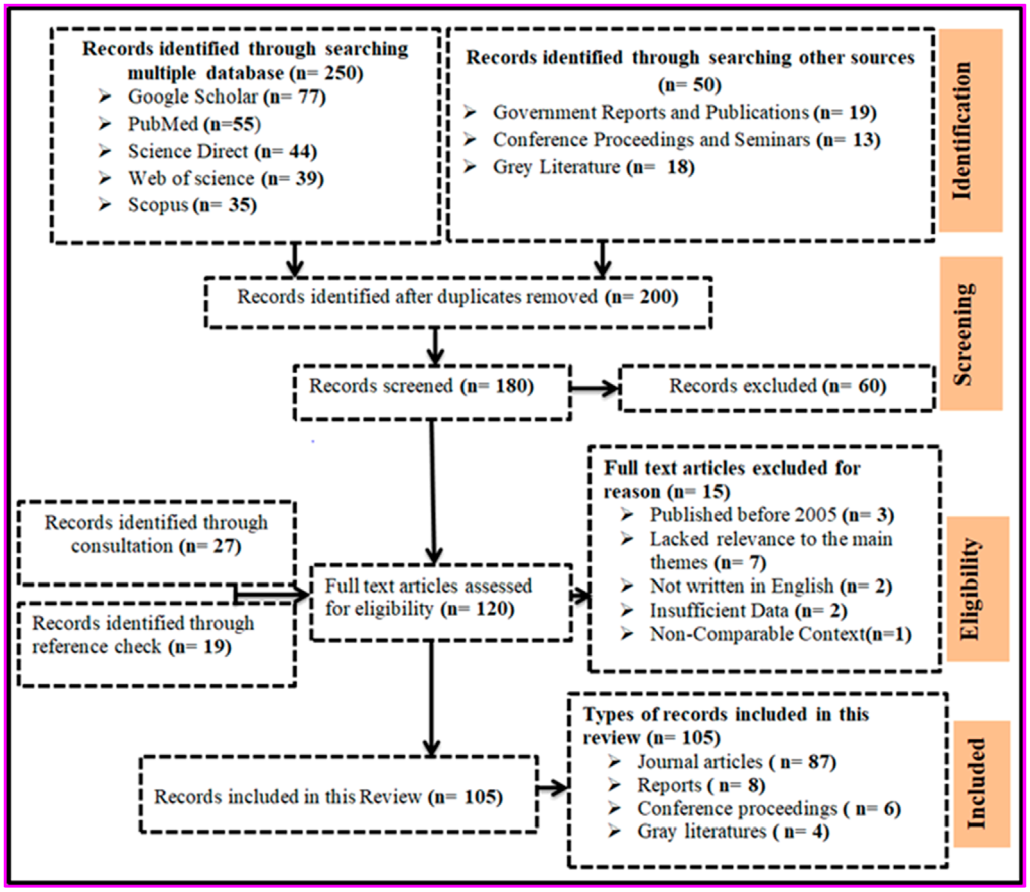

FIGURE 1
PRISMA flow diagram of the included studies.

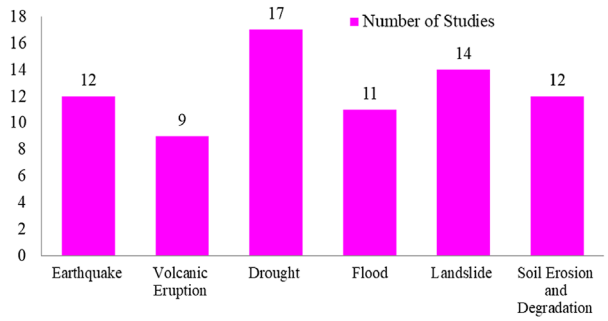

FIGURE 2
Thematic distribution of included studies.

3.1.2 Temporal distribution of included literature

The temporal distribution of the included studies reveals a clear upward trend in research on geological and hydrometeorological hazards affecting livestock production in Ethiopia. Figure 3 illustrates this trend. Between 2005 and 2010, only 13 studies (12.4%) of the reviewed literature were published, reflecting limited academic and policy focus on the subject. From 2011 to 2020, the number of studies increased significantly, accounting for 50 studies (47.6%) of the total, coinciding with growing concerns over climate change and its impacts on pastoral and agro-pastoral communities. The most substantial growth occurred between 2021 and 2025, with 47 studies (44.8%) published, indicating heightened scholarly and governmental interest in hazard mitigation and adaptation strategies. An analysis of thematic focus over time shows a shift in research priorities. Prior to 2010, most studies concentrated on drought (60%) and general climate variability, with limited attention to other hazards. Between 2011 and 2020, research expanded to include floods, soil erosion, and landslides, reflecting increasing recognition of multi-hazard risks. More recent studies (2021–2025) have incorporated emerging threats such as volcanic eruptions and earthquakes, though these remain less studied compared to hydrometeorological hazards. Earlier studies (2005–2010) primarily documented the impacts of hazards on livestock production, with limited discussion on adaptation strategies. From 2011 to 2020, research began to emphasize resilience-building measures, including sustainable rangeland management and early warning systems. The latest studies (2021–2025) focus more on integrated adaptation approaches, combining scientific advancements, policy interventions, and indigenous knowledge systems. While the volume of research has increased over the past two decades, significant gaps remain.

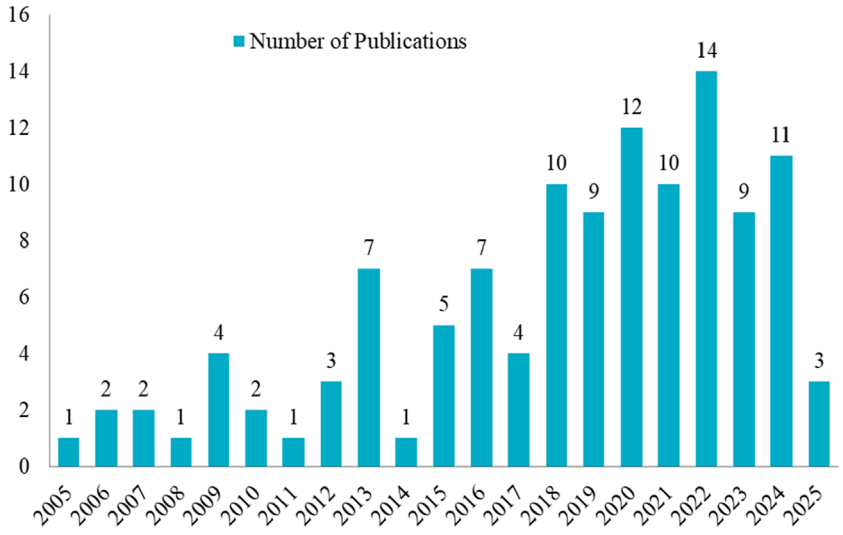

FIGURE 3
Temporal distribution of included literature.

The lack of long-term empirical studies assessing hazard impacts on livestock productivity limits the ability to develop predictive models. Furthermore, interdisciplinary research linking geological and hydrometeorological hazards with socio-economic resilience in pastoral systems is still underdeveloped. Addressing these gaps through longitudinal studies and multi-sectoral collaborations is crucial for enhancing Ethiopia's livestock sector resilience. The findings highlight a growing research interest in livestock-related hazard impacts, with a notable shift from impact assessment to adaptation-focused studies over time. However, continued efforts are needed to ensure comprehensive, data-driven policies that address both immediate and long-term threats to Ethiopia's livestock sector.

3.2 Geological and hydrometeorological hazards affecting livestock production in Ethiopia

Ethiopia's position within the East African Rift System makes it a region of intense geologic activity, with frequent earthquakes, volcanic eruptions, landslides, and soil erosion. These geologic hazards have significant implications for the country's agricultural systems, particularly livestock production, which is central to the livelihoods of millions of Ethiopians. The interplay of tectonic movements, volcanic activity, and weather patterns exacerbates the vulnerability of livestock to these natural disasters. Below, we explore the major geologic hazards in Ethiopia, focusing on their frequency, regional variation, and impact on livestock production.

3.2.1 Earthquakes

Ethiopia's position within the tectonically active East African Rift System renders it highly susceptible to seismic disturbances, with significant earthquake activity concentrated in regions such as the Afar Depression, the Southern Rift, and the Bale Mountains (Mebrahtu et al., 2020). The dense clustering of seismic events along the rift zones, particularly within the Afar region and extending through the Ethiopian Rift Valley, highlights the region's active tectonic setting and the ongoing divergence of the African and Arabian plates (Lemenkova, 2022). Ayele (2017) attributes this heightened seismicity to the ongoing divergence of the Arabian, Somali, and Nubian plates, which drives faulting, crustal deformation, and periodic ground displacement. The Afder Zone and the Southern Rift, situated along these tectonic boundaries, frequently experience moderate to high-magnitude earthquakes, although their intensity generally remains lower compared to seismically active zones such as the Kenyan Rift Valley (Fentahun et al., 2021). The repercussions of seismic activity on livestock-based livelihoods are substantial. Earthquakes often inflict structural damage on critical infrastructure, including transportation networks, water wells, and livestock enclosures, disrupting market access and limiting pastoralists' ability to secure essential resources (Girma et al., 2012). The Bale Mountains region is particularly vulnerable to secondary hazards, such as landslides, which exacerbate these disruptions by degrading pasturelands and displacing animals (Fentahun et al., 2021). Additionally, seismic activity modifies regional hydrology by altering groundwater pathways, affecting the availability of drinking water an issue of particular concern in drought-prone lowland areas (Fubelli and Dramis, 2015). Topographical shifts triggered by earthquakes further fragment grazing lands, compelling pastoralists to either migrate in search of new pastures heightening competition and resource conflicts or reduce herd sizes, directly undermining economic stability (Ayele et al., 2021).

The Afar Depression, one of Ethiopia's most seismically volatile regions, presents even greater challenges (Ayele et al., 2016). As depicted in the map, tectonic interactions between the Red Sea and Gulf of Aden rift systems contribute to persistent seismic activity, intensifying vulnerabilities in livestock production (Ayele, 2017). Here, land subsidence and surface fissuring driven by tectonic

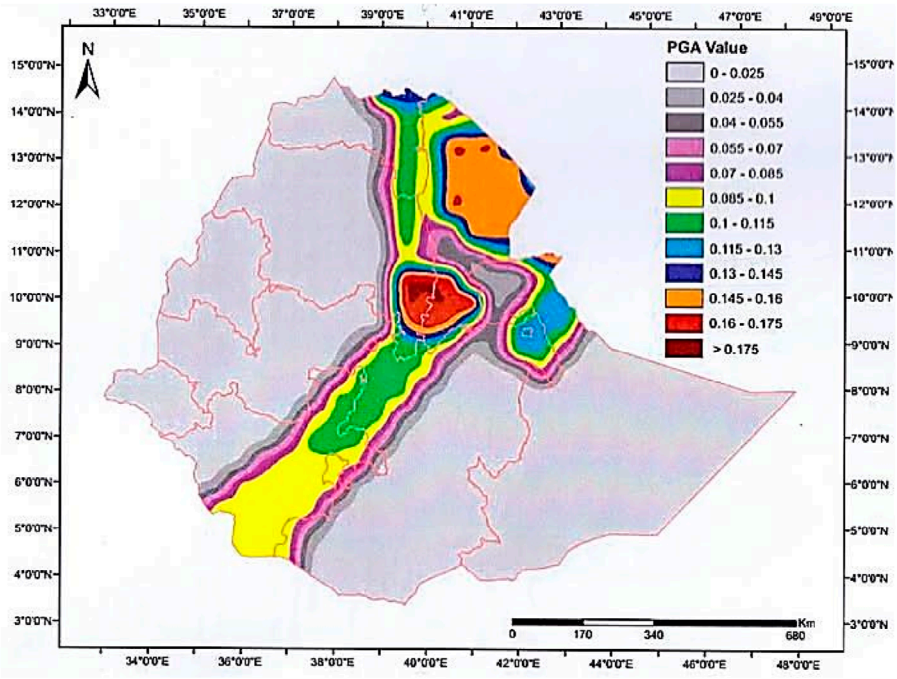

FIGURE 4
Ethiopia's seismic hazard in terms of peak ground acceleration (PGA) according to the new code of practice [Civil Engineering Students Computer Aided Research Team (CESCART) (2020)].

shifts frequently degrade pasture availability, compounding existing pressures on livestock-dependent communities (Fentahun et al., 2021). Furthermore, seismic disturbances induce physiological stress in animals, leading to reduced reproductive efficiency, increased disease susceptibility, and diminished productivity (Vaitla et al., 2012). To mitigate these risks, Ethiopian pastoral communities have historically relied on mobility-based adaptation strategies, economic diversification, and indigenous knowledge systems to anticipate and respond to seismic hazards (Lemenkova, 2022). However, the effectiveness of these approaches is increasingly constrained by land-use fragmentation, population growth, and limited governmental investment in infrastructure resilience (Mebrahtu et al., 2020). Addressing these challenges requires strengthening earthquake-resistant infrastructure, enhancing early warning systems, and fostering regional collaboration in seismic monitoring. Strategic interventions in these areas could significantly bolster the adaptive capacity of Ethiopia's livestock sector, ensuring greater resilience in the face of persistent tectonic activity (Girma et al., 2012). Figure 4 illustrates the spatial distribution of seismic hazard levels across Ethiopia based on peak ground acceleration (PGA) values as defined in the latest national seismic code of practice. The map highlights regions with varying degrees of seismic risk, with higher PGA values concentrated along the East African Rift System, particularly in the Afar Depression, the Ethiopian Rift Valley, and parts of the Southern Rift. Areas with elevated seismic activity correspond to major tectonic boundaries where the Arabian, Nubian, and Somali plates interact, leading to frequent faulting and ground displacement. The classification of seismic hazard zones in the figure provides a critical reference for infrastructure planning, earthquake-resistant construction, and disaster risk management strategies in Ethiopia.

3.2.2 Volcanic eruptions

Ethiopia's geological landscape is shaped by its position along the East African Rift, making it one of the most volcanically active regions in Africa (Clarke et al., 2020). The country hosts several active and dormant volcanoes, primarily concentrated in the Afar Depression and the Rift Valley (Tadesse et al., 2019). As illustrated in Figure 5, prominent volcanoes such as Erta Ale, Dallol, Alayta, Fentale, and Tullu Moje pose significant hazards to livestock production due to eruptions, toxic gas emissions, and the alteration of grazing landscapes. Volcanic eruptions exert immediate and often catastrophic effects on livestock populations. Lava flows, pyroclastic surges, and explosive eruptions destroy grazing land and displace pastoral communities (Vye-Brown et al., 2016). Erta Ale, known for its persistent lava lake, presents a continuous hazard due to periodic eruptions that threaten nearby settlements (Demissie et al., 2023). The Dallol Depression, one of the most geologically active areas in Ethiopia, emits toxic gases, including sulfur dioxide and hydrogen sulfide, which can be lethal to livestock and degrade the quality of pasturelands (Ayonghe and Wantim, 2019). In addition to immediate destruction, volcanic eruptions contribute to long-term environmental degradation, affecting water availability and pasture fertility (Mazzarini et al., 2016). Volcanic ashfall, a major consequence of explosive eruptions, blankets grazing areas and reduces their nutritional quality (Solomon and Belete, 2019). According to Tierz et al. (2020), ash deposition alters soil pH and mineral composition, leading to reduced forage availability for livestock. The eruption of Fentale Volcano, located in the

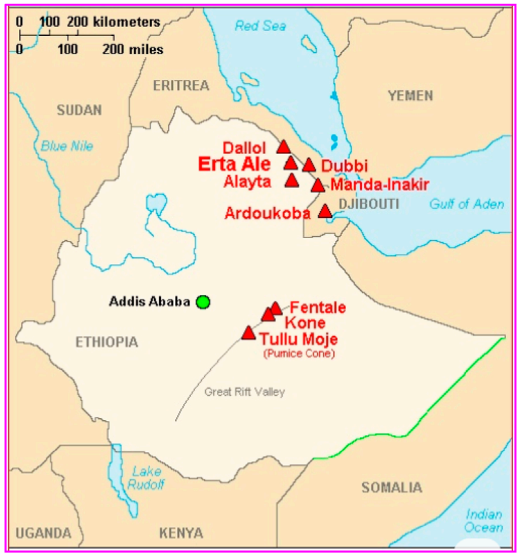

FIGURE 5
Major volcanoes of Ethiopia (USGS, 2003).

central Rift Valley, had a lasting impact on pastoral communities by disrupting traditional grazing routes and contaminating local water sources (Vye-Brown et al., 2016). Furthermore, volcanic activity influences hydrological systems (Solomon and Belete, 2019). The Manda-Inakir and Ardoukoba volcanic regions, situated along the Ethiopia-Djibouti border, contribute to hydrothermal alterations in groundwater systems (USGS, 2003). These changes lead to increased salinity and contamination of drinking water sources for livestock, further exacerbating water stress in already arid regions (Clarke et al., 2020). Volcanic hazards significantly disrupt the livelihoods of pastoralists and agro-pastoral communities, necessitating costly adaptations. Livestock mortality due to exposure to toxic gases, respiratory distress, and loss of grazing land forces communities to migrate in search of alternative pastures, often leading to conflict over resources (Demissie et al., 2023). Moreover, the destruction of infrastructure, including roads and market access points, isolates affected communities from essential veterinary and feed supply chains, exacerbating economic vulnerability (Fubelli and Dramis, 2015).

3.2.3 Landslides and rockfalls

Ethiopia's highland regions, particularly the Ethiopian Highlands and the Bale Mountains, are highly susceptible to landslides and rockfalls, primarily during the rainy season (Martínek et al., 2021). The combination of steep slopes, heavy rainfall, and underlying geological instability significantly contributes to mass movements of soil and rock in these regions (Mazzarini et al., 2016). As shown in the attached figure, areas marked in red and blue indicate high to moderate susceptibility to landslides, particularly in the northwestern and southwestern highlands (Figure 6). The distribution of pink dots further highlights frequent landslide occurrences, particularly in key livestock production zones. Landslides in Ethiopia are triggered by multiple factors, including intense precipitation, deforestation, soil degradation, and seismic activity (Mewa and Mengistu, 2022). The Ethiopian Highlands, characterized by steep terrain and loose soil, frequently experience rapid landslides, particularly following prolonged rainfall events (Mebrahtu et al., 2020). These hazards not only pose a direct threat to human settlements but also severely impact livestock production by destroying pasturelands, blocking water sources, and damaging essential infrastructure such as animal shelters and feeding stations (Tesfa, 2024). In hilly and mountainous terrains, where livestock grazing is a primary activity, landslides can bury vast areas of pasture, rendering them unusable (Mewa and Mengistu, 2022). Rockfalls and debris flows further exacerbate the situation by creating physical barriers that obstruct livestock movement and migration routes (Tadesse et al., 2024). This disruption is particularly devastating for pastoral communities that rely on seasonal migration to access grazing lands and water points. Martínek et al. (2021) highlight that landslides also damage key infrastructure, such as water troughs, fences, and veterinary posts, further isolating communities and reducing their ability to care for livestock.

Several regions in Ethiopia have been identified as landslide-prone, particularly the northwestern highlands (Gojjam, Gondar, and Wollo), parts of central Ethiopia (Shewa), and the southeastern Bale Mountains (Mewa and Mengistu, 2022). The Bale Mountains, for instance, frequently experience landslides due to a combination of seismic tremors and intense rainfall, leading to soil instability and mass movement (Mebrahtu, 2021). Additionally, the northwestern regions exhibit high landslide susceptibility due to active fault lines and seasonal heavy rains, as depicted in the Given figure (Figure 6). Landslides in these areas disrupt not only human settlements but also critical grazing zones, reducing feed availability and forcing livestock owners to relocate (Tesfa, 2024). Beyond the immediate destruction caused by landslides and rockfalls, these hazards contribute to long-term environmental degradation. The loss of fertile topsoil due to landslides reduces the productivity of grazing lands, necessitating alternative livestock feeding strategies (Wang et al., 2024). Furthermore, blocked rivers and water channels lead to the formation of stagnant pools, increasing the risk of waterborne diseases among livestock (Wendim et al., 2023). Adaptive strategies to mitigate the impact of landslides on livestock production include improved land-use planning, afforestation programs to stabilize slopes, and the development of early warning systems for at-risk communities (Woldearegay, 2013). Sustainable grazing practices, such as rotational grazing and controlled livestock movement, can also help reduce the vulnerability of pastoralists to landslide-related disruptions (Martínek et al., 2021). Investments in resilient infrastructure, including reinforced animal shelters and protected water sources, are essential for minimizing the long-term impacts of these geological hazards on Ethiopia's livestock sector (Mewa and Mengistu, 2022). In conclusion, landslides and rockfalls pose a significant threat to livestock production in Ethiopia, particularly in highland regions. As shown in Figure 6, landslides are primarily concentrated in the highland regions of Ethiopia, which also host a substantial portion of the country's livestock population.

3.2.4 Flooding

Flooding represents a significant hydrometeorological hazard to livestock production in Ethiopia, although it occurs less

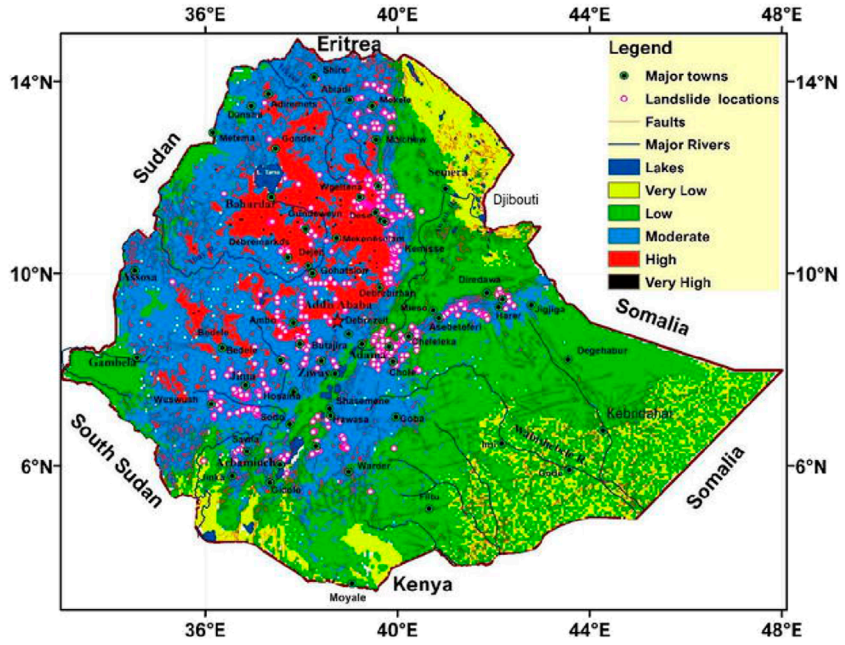

FIGURE 6
Distribution of landslides in Ethiopia (Mewa and Mengistu, 2022).

frequently than droughts (Dixit and Balasubramanian, 2006). Despite its lower frequency, the consequences of flooding can be catastrophic, especially in the lowland and riverine regions where livestock-dependent pastoral communities are concentrated (Ogato et al., 2020). Flood events, though sporadic, can result in widespread damage, including the destruction of grazing lands, contamination of water sources, and displacement of both livestock and people (Wondim, 2016). As a result, pastoralist communities experience severe disruptions to their food and water security (Sinshaw et al., 2018). One of the most devastating flood events occurred in 2006 in the Southern Nations, Nationalities, and Peoples' Region (SNNPR), which led to the death of approximately 15,600 livestock (UNOCHA, 2006). This incident highlights the extreme vulnerability of livestock populations to flooding and serves as a case study of the devastating impact of such events. Flooding in Ethiopia is often a result of hydrometeorological phenomena such as heavy seasonal rains, rapid snowmelt from the Ethiopian highlands, or the failure of natural or artificial dams along major river systems such as the Awash, Omo, and Baro Rivers (Okunola and Simatele, 2022). Geological factors, including landslides and seismic activity, further exacerbate the frequency and intensity of floods, compounding the challenges faced by pastoral communities (Ogato et al., 2020). The vulnerability of livestock production to flooding is most apparent in flood-prone regions such as Somali, where pastoral and agro-pastoral communities rely heavily on livestock for their livelihood (Arnold et al., 2018). In recent years, floods have resulted in the loss of significant numbers of livestock, exacerbating food insecurity and undermining the economic stability of affected households. For instance, floods in 2024 led to the loss of 1,150 animals in affected areas (WHO, 2024), showcasing the recurring nature of flood-related impacts. Moreover, the destruction of vital infrastructure, including irrigation systems and roads, hinders access to veterinary services and markets, further contributing to the vulnerability of livestock populations (WHO, 2024).

Floods bring a host of direct and indirect consequences. The contamination of grazing lands and water sources with pathogens and parasites significantly impacts livestock health (Alemu and Mengistu, 2019). Pathogens introduced by floodwaters increase the incidence of diseases such as cholera, leptospirosis, and anthrax, which in turn lead to high mortality rates in livestock populations (Wondim, 2016). In addition to health risks, floods disrupt access to veterinary care and hinder market activities, resulting in economic losses and undermining the livelihoods of pastoralists (Amsalu and Adem, 2009). The erosion of grazing lands, particularly along the Baro and Omo rivers, further exacerbates the long-term impacts of flooding (Ayele et al., 2020). The loss of fertile soils and the alteration of the topography in flood-affected areas contribute to the deterioration of pasturelands, leaving livestock vulnerable to food shortages during dry periods (Bogale and Erena, 2022). Moreover, the stagnant water bodies created by flooding provide ideal breeding grounds for disease-carrying insects, thereby increasing the prevalence of vector-borne diseases and further jeopardizing livestock health (Tesfa, 2024). Mitigation efforts to address the impacts of flooding on livestock production have included the development of flood forecasting systems and flood protection infrastructure (Bogale and Erena, 2022). While progress has been made in improving flood prediction and early warning systems, the unpredictability of flooding events presents a significant challenge to pastoral communities (Demissie et al., 2021). Flood preparedness and response strategies, including both structural measures such as flood barriers and non-structural approaches like community-based

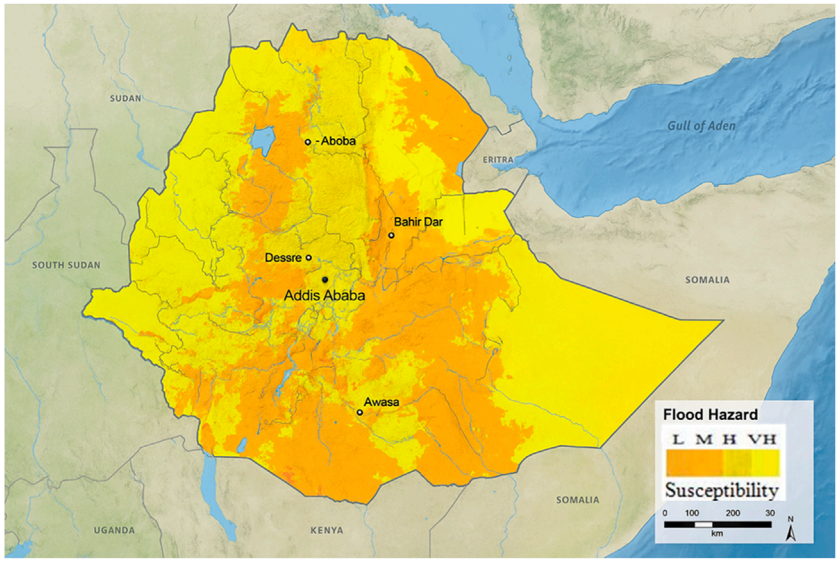

FIGURE 7
Flood suscestaiblity map of Ethiopia (World Bank, 2019, p.9).

disaster management, are essential for building resilience in flood-prone regions (Okunola and Simatele, 2022). Furthermore, the integration of indigenous knowledge and modern flood mitigation practices could enhance the sustainability of these interventions, offering more effective solutions for safeguarding livestock-dependent livelihoods (Demissie et al., 2023). In conclusion, the impacts of flooding on livestock production in Ethiopia are far-reaching, affecting both the immediate and long-term viability of pastoralist systems. A comprehensive approach to flood management, integrating advanced technological solutions with community-based strategies and local knowledge, is vital for strengthening resilience and reducing vulnerability in flood-prone regions. Enhanced infrastructure, combined with adaptive livestock management practices and government support, are key to mitigating the negative effects of flooding and ensuring the sustainability of livestock production in Ethiopia. Figure 7 illustrates the major flood-affected areas of Ethiopia, underscoring the cyclical nature of flooding and its ongoing impact on livestock and pastoral livelihoods.

3.2.5 Drought

Droughts in Ethiopia represent one of the most severe and recurring hazards, profoundly affecting livestock production. Between 2020 and 2023, the country endured five consecutive failed rainy seasons, resulting in the loss of 6.8 million livestock, which has severely impacted the livelihoods of pastoral and agro-pastoral communities (FAO, 2023, June 6). These prolonged drought conditions led to an acute shortage of water and feed resources, undermining the health and productivity of livestock (Habte et al., 2022). As pasturelands dried up, livestock suffered from malnutrition, and in many instances, entire herds perished due to the inability to access adequate grazing areas (Mulugeta, 2023). The economic repercussions of such severe droughts are profound. Livestock, a critical asset for rural Ethiopian families, provides income, food, and cultural value. When drought decimates livestock populations, the financial stability of families is compromised, and the broader rural economy suffers (Bogale and Erena, 2022). The devastating impact of droughts is compounded by the scarcity of water, as rivers, ponds, and wells often dry up during extended dry periods. This makes survival increasingly difficult for livestock, and pastoral communities are forced to travel longer distances to access water and grazing areas (Abdela, 2024). This increased mobility not only stresses both animals and people but also exacerbates the challenges of maintaining livestock health and productivity (Habte et al., 2022). As depicted in Figure 8, the drought affecting the livestock of Borana Zone in October 2022 illustrates the profound challenges posed by water and forage shortages for pastoralist communities in the region.

The consequences of recurring droughts extend beyond immediate economic loss to have long-term effects on the resilience of pastoral systems. The ongoing depletion of water resources and grazing lands from repeated drought events reduces the capacity of livestock systems to recover, increasing vulnerability over time (Teku and Eshetu, 2024). Droughts also lead to declines in both the quantity and quality of livestock, further weakening the Ethiopian economy, where livestock production is a cornerstone of agricultural activity (Alemu and Mengistu, 2019). In response to these challenges, several mitigation strategies have been proposed, including the establishment of early warning systems, water harvesting technologies, and the development of drought-resistant forage crops (Teku and Eshetu, 2024). These initiatives aim to reduce the impact of droughts on livestock health and productivity. However, successful adaptation requires integrated approaches that consider ecological, economic, and social dimensions of pastoral systems (Amsalu and Adem, 2009). While some strategies, such as

FIGURE 8
Drought impact on the livestock of Borana Zone in October 2022 (Bogale and Erena, 2022).

improved water management and the introduction of drought-resistant species have shown promise, they remain insufficient without consistent investment in research, extension services, and community capacity-building to enhance the resilience of livestock systems (Ayele et al., 2020). Despite these efforts, the cyclical nature of droughts continues to strain Ethiopia's livestock sector. The challenge remains in strengthening both the capacity of communities to adapt to these extreme conditions and the government's ability to provide timely support through effective policies and interventions (Bogale and Erena, 2022). Without sustained and expanded adaptation efforts, droughts will continue to pose a significant and recurring threat to livestock production in Ethiopia, with profound implications for rural livelihoods and national food security (Gezie, 2019). As shown in Figure 9, the drought probability distribution in Ethiopia illustrates the varying levels of drought risk across different regions of the country. This distribution directly impacts livestock, as areas with higher drought probability experience severe water shortages and forage scarcity, leading to reduced livestock health, higher mortality rates, and diminished productivity, particularly in pastoralist communities that rely heavily on livestock for their livelihoods. As shown in Figure 10, the land degradation classification in Ethiopia underscores the areas most impacted by soil erosion and degradation, which significantly affect livestock grazing lands and contribute to reduced pasture availability and quality for pastoralist communities.

3.2.6 Soil erosion and land degradation

Soil erosion and land degradation pose significant challenges to livestock production in Ethiopia, with both natural and anthropogenic factors driving these processes (Teku et al., 2024a). Soil erosion is particularly severe in the Ethiopian Highlands, where heavy rainfall, seismic shifts, and volcanic activity exacerbate the degradation of grazing lands (Wolka et al., 2015). The impact of soil erosion is compounded by unsustainable agricultural practices, such as deforestation and overgrazing, which accelerate the process and reduce the quality of the land for livestock grazing (Teku et al., 2024b). Quantitative data illustrates the severity of this issue. According to Tamene et al. (2022), approximately 2.7 billion tons of soil are lost from Ethiopia's highlands annually due to erosion, with a substantial portion of this loss occurring in areas that are critical for livestock grazing. This large-scale soil loss directly contributes to reduced soil fertility, further depleting the resources that support livestock production (Teku and Derbib, 2025). The erosion of topsoil, particularly in the volcanic regions, leads to rapid degradation, which in turn reduces the availability of high-quality pasture and forage for livestock (Teku and Workie, 2025). The consequences of this are evident in declining livestock productivity, as animals suffer from malnutrition due to the insufficient supply of quality grazing land.

The Ethiopian Highlands, where pastoralism is central to the livelihood of rural communities, are particularly vulnerable to the effects of soil erosion (Tamene et al., 2022). As Buraka et al. (2024) highlight, the depletion of grazing lands forces pastoralists to move livestock farther in search of adequate grazing areas. This migration often leads to further stress on the animals and increases competition for limited resources (Tsegaye, 2019). Additionally, these regions are prone to other geological hazards, such as landslides and seismic events, which compound the challenges faced by pastoral communities (Tadesse and Hailu, 2024). As soils degrade, pastoralists find themselves trapped in a vicious cycle where the loss of grazing land and the increased difficulty in finding water and feed further strain the health and productivity of their livestock (Wolka et al., 2015). Another significant impact of soil erosion is the siltation of water sources. The erosion of soils into nearby rivers, streams, and ponds leads to the contamination and reduction of clean water supplies, which are essential for livestock survival. Saguye (2017) notes that this process severely affects the availability of clean water during dry periods, exacerbating the vulnerability of livestock to dehydration and disease outbreaks. Moreover, the erosion-induced reduction in soil fertility also affects the growth of fodder crops, further diminishing the food supply for livestock, particularly during the lean seasons. These combined factors have far-reaching consequences for livestock productivity (Battistelli et al., 2022). The degraded grazing lands result in stunted growth and poor health among livestock, reducing their market value and productivity (Tadesse and Hailu, 2024). As a result, the economic stability of pastoral communities is jeopardized, leading to increased poverty and food insecurity. In areas where soil erosion has severely affected the land, the overall carrying capacity for livestock has declined, forcing communities to adopt costly mitigation measures, such as purchasing feed and water from external sources, which further strains their economic resources (Nyssen et al., 2008). In conclusion, soil erosion and land degradation in Ethiopia are significant drivers of livestock production decline, with profound implications for pastoral livelihoods (Tadesse and Hailu, 2024; Tamene et al., 2022; Wolka et al., 2015). The environmental degradation caused by soil erosion not only reduces the quantity and quality of grazing land but also leads to water scarcity, reduced fodder availability, and the disruption of livestock health (Teku and Eshetu, 2024). Addressing these challenges requires comprehensive land

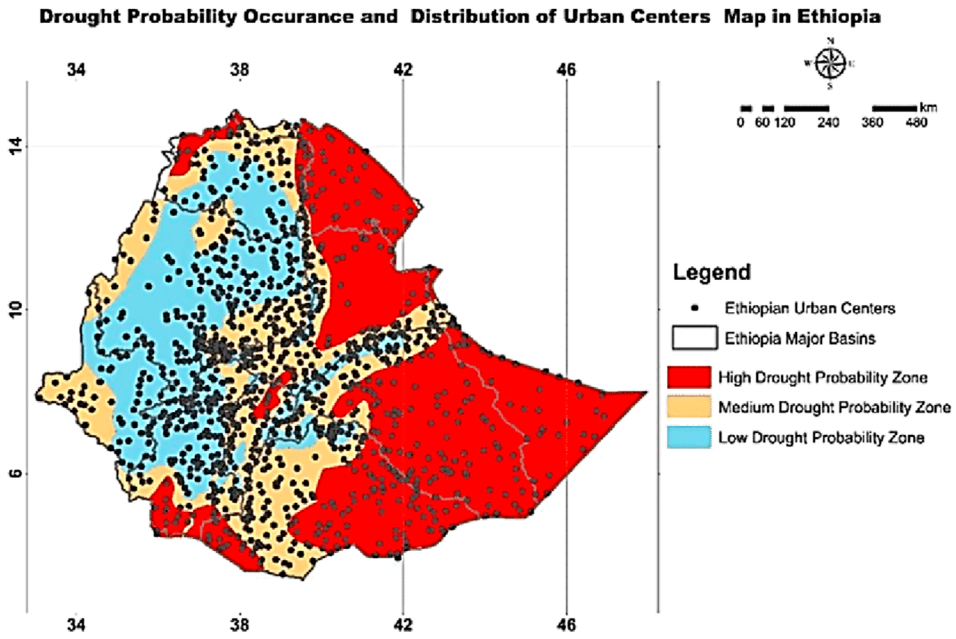

FIGURE 9
Drought probability distribution map of Ethiopia [National Meteorological Agency (2007) in Abraha et al., 2022].

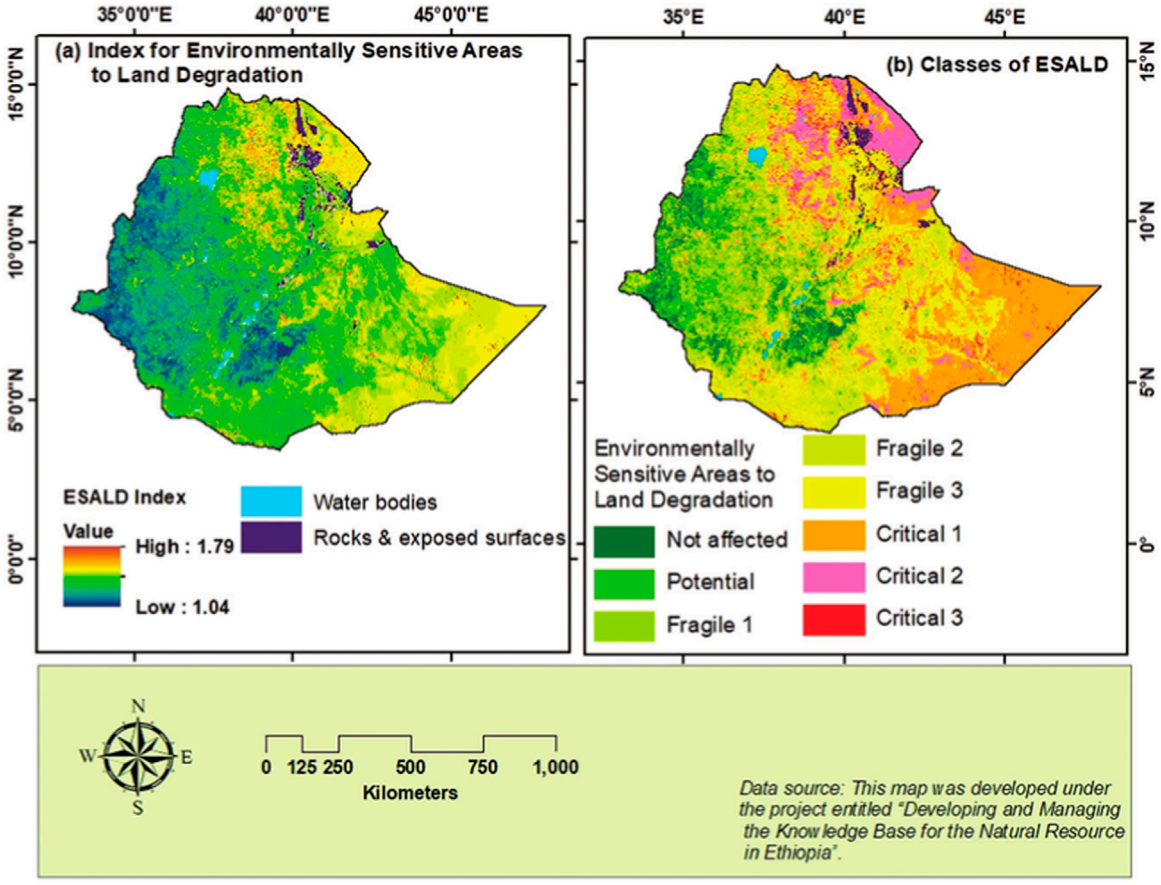

FIGURE 10
Environmentally sensitive areas to land degradation in Ethiopia (Teferi et al., 2023).

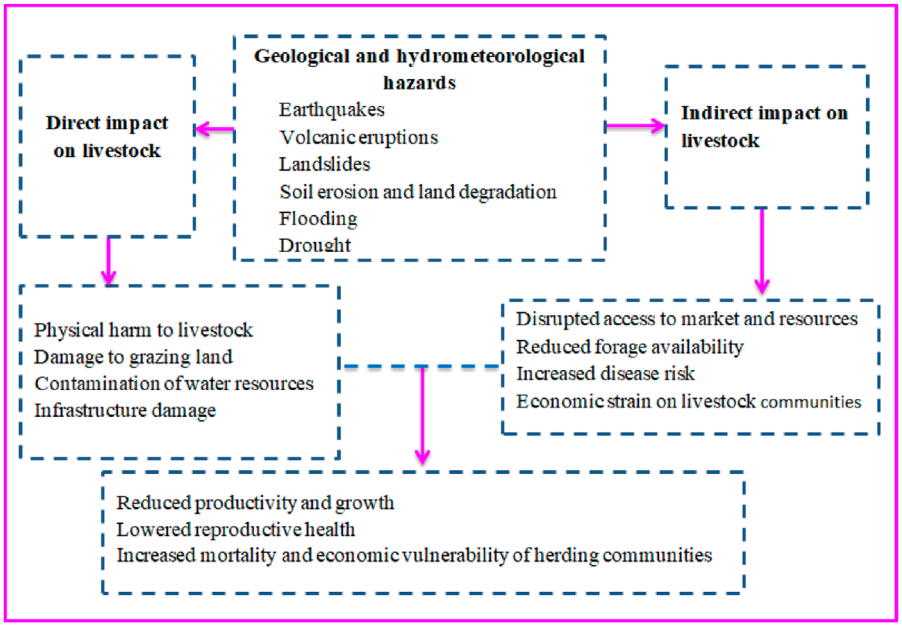

FIGURE 11
Summary of key geological and hydrometeorological hazards and their impacts on livestock production in Ethiopia (compiled by the authors).

management strategies that focus on both preventing further degradation and rehabilitating affected areas to restore their productivity.

3.3 Impact of geological and hydrometeorological hazards on livestock productivity, health, and market systems

Geologic hazards such as volcanic eruptions, earthquakes, landslides, and soil degradation have profound and often cascading effects on livestock production in Ethiopia (Abdela, 2024; Amenu, 2013; Martínek et al., 2021). These hazards disrupt essential elements of livestock management, including grazing lands, water sources, veterinary services, and pasture productivity, directly influencing livestock health, nutrition, and mobility (Fubelli and Dramis, 2015). The interplay of seismic activity, volcanic forces, and soil erosion exacerbates the vulnerability of livestock, contributing to disease outbreaks, malnutrition, and resource depletion, ultimately affecting the livelihoods of pastoral communities (Ogato, 2013). This section comprehensively examines how these geologic hazards impact livestock production, focusing on livestock health, pasture and water resource degradation, and livestock displacement (Solomon and Belete, 2019). As shown in Figure 11, key geological and hydrometeorological hazards in Ethiopia, such as floods, droughts, and soil erosion, significantly affect livestock production, exacerbating challenges for pastoral communities.

3.3.1 Livestock health

Livestock health in geologically active regions like Ethiopia is highly vulnerable to hazards such as volcanic ash, earthquakes, and landslides, which disrupt the environment and access to essential resources (World Bank, 2018). The deposition of volcanic ash can cause severe respiratory problems as livestock inhale fine ash particles. Weldeslassie et al. (2018) highlight that ash from active volcanoes such as Erta Ale and the Dallol Depression can blanket vast areas, reducing air quality and making breathing difficult for animals. Ingestion of ash-covered forage exposes cattle to toxic substances, increasing the risk of gastrointestinal disorders or poisoning (Kebede et al., 2018). Contamination of water sources further compounds the problem by introducing harmful chemicals, reducing water quality, and making it unsafe for both drinking and irrigation (Middleton, 2009). Earthquakes, particularly in the Southern Rift and Afder Zone, can cause the collapse of veterinary clinics, livestock shelters, and water storage systems, limiting access to timely medical care and clean water (Ayele et al., 2016). Additionally, landslides triggered by seismic activity can bury grazing areas, creating immediate barriers to movement and food access (Lemenkova, 2022). These events also cause soil liquefaction and water source damage, further complicating veterinary and livestock care (Girma et al., 2012). The destruction of veterinary infrastructure, as noted by Skinner (2007), leads to delays in disease treatment and increases the risk of zoonotic disease outbreaks and livestock mortality. Geologic hazards also exacerbate the spread of diseases, particularly in areas with limited veterinary services (Teku and Eshetu, 2024). Earthquakes, landslides, and volcanic eruptions disrupt livestock movement patterns, causing the intermingling of previously isolated herds and increasing the risk of disease transmission, including highly contagious infections like foot and mouth disease and anthrax (Martínek et al., 2021). Furthermore, disruptions in water and feed supply due to volcanic ash or landslides weaken livestock immune systems, making them more susceptible to infections and diseases (Fubelli and Dramis, 2015). Beyond these,

geohazards have deep psychosocial effects on livestock producers. Studies reveal that sudden livestock deaths due to landslides, flooding, or volcanic eruptions cause emotional distress, anxiety, and long-term mental health challenges among pastoralists and agro-pastoralists (Ayele et al., 2016). These losses disrupt social cohesion and traditional systems of mutual support, eroding the overall social wellbeing of affected communities.

3.3.2 Pasture and water resource degradation

Pastureland and water resources are vital for livestock survival, yet geologic hazards significantly impact their availability and quality. Soil erosion, driven by volcanic activity, heavy rainfall, and seismic disturbances, leads to the destruction of grazing lands (Tadesse and Hailu, 2024). Volcanic ash deposits in regions like the Danakil Depression and Ethiopian Highlands accelerate erosion by displacing topsoil, reducing soil fertility, and impairing vegetation growth essential for grazing (Tamene et al., 2022). The continuous loss of nutrient-rich topsoil diminishes pasture productivity, limiting forage availability and causing nutritional deficits for livestock, particularly during droughts (Saguye, 2017). Earthquakes contribute to land subsidence, where the sinking or settling of the ground disrupts grazing land integrity (Fubelli and Dramis, 2015). In seismically active areas such as the Southern Rift and Bale Mountains, tectonic shifts alter land elevation, transforming productive grazing zones into barren or waterlogged regions (Fentahun et al., 2021). This loss of pastureland intensifies competition for limited resources while also altering watercourses, reducing livestock access to water sources (Ayele et al., 2016). Volcanic eruptions further degrade water quality, posing serious risks to livestock health. Frequent eruptions in the Erta Ale and Dallol volcanic fields release gases and minerals that contaminate nearby water sources, rendering them unsafe for consumption and leading to dehydration and health complications (Weldeslassie et al., 2018; Kebede et al., 2018). Even when eruptions occur far from grazing areas, volcanic ash can travel long distances, contaminating river systems and springs relied upon by pastoralists. As Vye-Brown et al. (2016) note, ash fallout can also clog wells and water reservoirs, further limiting the availability of potable water for livestock.

3.3.3 Displacement of livestock

The displacement of livestock due to geologic hazards is a common challenge in Ethiopia's geologically active regions, forcing animals to migrate in search of food, water, and safer conditions (Fubelli and Dramis, 2015). This movement creates significant challenges for livestock owners, particularly in managing grazing resources, maintaining animal health, and preventing conflicts over land use. When earthquakes, volcanic eruptions, or landslides destroy grazing lands or water sources, livestock communities must relocate their animals, often leading to overgrazing in new areas (Mewa and Mengistu, 2022). This increased pressure on already fragile ecosystems intensifies land degradation, as livestock compete for limited grazing resources. Migration into new territories can also create tensions between pastoralist communities, further complicating the sustainable management of grazing lands (Amsalu and Adem, 2009). The increased demand for pastureland following displacement accelerates soil erosion and land degradation, particularly in regions such as the Bale Mountains and the Southern Rift, where geologic hazards frequently push large numbers of animals into already stressed ecosystems. As grazing lands become overused, pasture quality declines, negatively impacting livestock health and productivity (Lumborg et al., 2021; Amenu, 2013). In addition to environmental challenges, displacement disrupts access to veterinary services, as herds are often moved into remote or less accessible areas. This limits disease monitoring and medical care, increasing livestock vulnerability to infections and malnutrition. The difficulty in tracking and treating displaced animals further complicates disease management efforts, exacerbating health risks for both livestock and pastoral communities (Amenu et al., 2013).

3.4 Vulnerability of livestock systems to geological and hydrometeorological hazards in Ethiopia

Ethiopia hosts a significant portion of Africa's pastoral and agro-pastoral communities, including the Oromo, Afar, and Somali pastoralists, as well as the Amhara and Tigray agro-pastoralists, whose livelihoods are deeply intertwined with livestock production (Mekuriaw and Harris-Coble, 2021). These communities face profound vulnerabilities due to a combination of geological hazards, such as earthquakes, volcanic eruptions, landslides, and soil erosion, along with the increasing impacts of climate variability (Abdela, 2024). These hazards exacerbate existing challenges, creating complex risks that threaten the sustainability of livestock systems, food security, and economic stability (Tofu et al., 2023). The interaction between geological hazards and climate change further amplifies these threats, increasing the pressure on pastoral and agro-pastoral communities (Lumborg et al., 2021). Pastoralists in Ethiopia, including the Oromo, Afar, and Somali communities, rely primarily on mobile herding, making them particularly susceptible to disruptions from geologic hazards (Mulugeta, 2023). The Afar people, living in the Danakil Depression, face significant risks from seismic activity and volcanic eruptions, particularly from Erta Ale, which alters landscapes, contaminates water sources, and forces migration to less suitable land, leading to overgrazing and resource conflicts (Fubelli and Dramis, 2015; Tofu et al., 2023). Similarly, Somali pastoralists in the Southern Rift experience rapid land degradation due to landslides and soil erosion, which destroy grazing lands and reduce livestock productivity (Ayonghe and Wantim, 2019). As pastoralism is deeply embedded in these communities' cultural and economic structures, any disruption to grazing patterns or water availability has immediate and long-term consequences (ILRI, 2023).

Agro-pastoralists, such as the Amhara and Tigray communities, practice a mix of crop cultivation and livestock rearing, offering a slightly more stable livelihood but still leaving them vulnerable to geologic hazards (Wendim et al., 2023). Landslides and soil erosion, often triggered by seismic activity or volcanic eruptions, reduce agricultural productivity and strain household economies. In regions like the Tigray Highlands, volcanic activity has contaminated water sources, severely limiting access to clean water for both human consumption and livestock (Ayonghe and Wantim, 2019). In general the review revealed that the combination of declining pastureland and compromised

water resources intensifies food insecurity and economic instability in Ethiopia. The compounding effects of geologic and hydrometeorological hazards highlight the urgent need for targeted mitigation strategies to safeguard Ethiopia's livestock-dependent communities from the escalating impacts of environmental and climatic changes.

3.5 Socio-economic and environmental consequences

The socio-economic and environmental consequences of geological and hydrometeorological hazards are discussed in this section. It highlights the broader impacts on rural communities, including loss of income, migration, food insecurity, and increased poverty. Additionally, the environmental degradation resulting from these hazards, such as soil erosion and reduced vegetation cover, is examined in relation to livestock sustainability.

3.5.1 Reduced livestock productivity

Geological and hydrometeorological hazards, including droughts, floods, soil erosion, and seismic activities, significantly impact livestock productivity in Ethiopia, leading to substantial economic losses for pastoral communities (Amenu, 2013). One of the most immediate consequences is the reduction of pastureland and depletion of water sources, directly affecting livestock nutrition and health (Ogato et al., 2020). For instance, during the prolonged 2020–2023 drought, Ethiopia endured five consecutive failed rainy seasons, resulting in the loss of 6.8 million livestock. As pasture availability declines and water sources dry up, livestock experience severe weight loss, reduced milk production, and increased mortality rates (Demissie et al., 2021). Malnutrition also weakens immune systems, making animals more susceptible to diseases and further reducing productivity (Ogato et al., 2020). The decline in livestock productivity disrupts rural economies, particularly in regions where pastoralism is the primary livelihood (Wondim, 2016). Reduced milk production not only affects household nutrition but also diminishes income from dairy sales (Eshetie et al., 2018). Livestock losses during extreme events, such as droughts and floods, can be devastating for families reliant on animals for sustenance and economic security (Habte et al., 2022). The 2006 floods in the Southern Nations, Nationalities, and Peoples' Region (SNNPR) resulted in the loss of 15,600 livestock (UNOCHA, 2006), highlighting the catastrophic impact of such events on pastoralist communities. The loss of cattle, goats, and sheep exacerbates food insecurity and economic vulnerability, pushing many households into deeper poverty (Lumborg et al., 2021).

Environmental degradation further compounds these challenges (Mekuriaw and Harris-Coble, 2021). Floods and soil erosion destroy pasturelands, reducing soil fertility and forcing pastoralists to seek alternative grazing areas, often at increased costs for feed and water (Mulugeta, 2023). This pressure depletes household income and financial stability, driving some pastoralists to abandon their herds entirely (Solomon and Belete, 2019). The cumulative effect of recurrent disasters leads to long-term reductions in livestock populations, negatively impacting the sustainability of the livestock sector (Sinshaw et al., 2018). Many affected communities are forced to seek alternative livelihoods or migrate to urban areas, where they face additional socio-economic challenges such as unemployment and loss of cultural identity, as pastoralism is deeply intertwined with Ethiopia's social fabric (Solomon and Belete, 2019). Geological hazards such as earthquakes, volcanic eruptions, and landslides also have direct and profound economic consequences for livestock-dependent communities. Livestock is not only a source of food and income but also a key asset representing household wealth and social status (Zegeye, 2018). Geological disturbances can lead to massive livestock losses, causing severe economic hardship for affected pastoralists (Solomon and Belete, 2019). Major geological events, such as earthquakes and volcanic eruptions, frequently result in livestock fatalities due to collapsing shelters, displacement, and contamination of grazing lands and water sources (Fubelli and Dramis, 2015). For example, the 2005 earthquake in Oromia's Rift Valley led to thousands of cattle, sheep, and goats perishing due to the destruction of grazing areas and water systems ((Solomon and Belete, 2019). Similarly, volcanic eruptions in the Danakil Depression have caused significant livestock losses due to toxic ash fall and pastureland destruction (Solomon and Belete, 2019). A 2010 eruption in the Afar region resulted in over 5,000 livestock deaths, demonstrating the devastating financial toll on pastoralist households (Tierz et al., 2020).

3.5.2 Disruptions to livestock trade and market stability

Beyond direct livestock losses, geological hazards disrupt trade and market access, exacerbating economic instability (Solomon and Belete, 2019). Landslides, soil erosion, and flood-related geological events damage critical infrastructure, including roads and transportation networks, restricting pastoralists' ability to move livestock to markets (Ali et al., 2025). A major landslide in the Amhara region in 2012 destroyed key trade routes, severely limiting market access and reducing livestock trade volumes (Mewa and Mengistu, 2022). As a result, many pastoralists were unable to sell their livestock, leading to reduced income and financial insecurity. Market confidence also declines in regions prone to seismic activity or volcanic eruptions, discouraging participation and lowering the demand for livestock products (Mebrahtu et al., 2020). Disruptions in supply chains and trade routes lead to price volatility, further destabilizing pastoral economies. For example, the 2011 eruption of Erta Ale disrupted trade networks and destroyed pasturelands, causing a sharp decline in livestock prices and compounding economic losses for local farmers (Girma et al., 2012).

Geological and hydrometeorological hazards also contribute to an increased burden of livestock diseases, which compound the negative impact on productivity and livelihoods (Nanyingi et al., 2015). Extreme weather events, such as floods and droughts, create favorable conditions for the spread of both vector-borne and waterborne diseases. For example, standing water from flooding can become a breeding ground for mosquitoes, which are responsible for transmitting diseases such as Rift Valley Fever (RVF). RVF outbreaks, which are often linked to periods of heavy rainfall, can cause high mortality rates in livestock, particularly in cattle

and sheep (Ikegami and Makino, 2011). The 2006 RVF outbreak in Ethiopia resulted in the deaths of thousands of animals and posed significant public health risks to humans, as the disease can also be transmitted to people through contact with infected animal tissues or fluids (Ibrahim et al., 2021). In addition to RVF, floods and stagnant water provide an ideal environment for the spread of waterborne diseases such as anthrax (Dixit and Balasubramanian, 2006). Anthrax spores can survive in the soil for many years and become more active when the soil is disturbed by floods or heavy rains (Yadeta et al., 2020). During these events, livestock may ingest contaminated water or graze on infected pasture, leading to outbreaks of the disease. The combination of floods, poor sanitation, and limited access to veterinary care makes it difficult to contain the spread of such diseases in rural areas, further exacerbating the vulnerability of pastoralists (Ibrahim et al., 2021).

The increased frequency and intensity of these diseases, exacerbated by climate change and geological hazards, pose a significant challenge to the health and productivity of livestock (Habte et al., 2022). Outbreaks of diseases like RVF and anthrax not only lead to direct losses in livestock but also place a financial burden on farmers who must pay for veterinary treatments, vaccinations, and disease control measures (Ibrahim et al., 2021). In some cases, entire herds may need to be culled to prevent the spread of disease, resulting in the loss of valuable assets and economic resources for pastoral families (Habte et al., 2022). The spread of livestock diseases also affects food security, as it leads to reduced availability of animal products such as milk, meat, and leather (Eshetie et al., 2018). In many rural areas of Ethiopia, livestock products are the primary source of protein and income, and the loss of animals due to disease can leave entire communities vulnerable to hunger and poverty (Mebrahtu et al., 2020). Additionally, disease outbreaks often necessitate quarantine measures and restrictions on livestock movement, disrupting traditional trade routes and access to markets (Solomon and Belete, 2019). This review highlights that addressing the increased disease burden requires improving early warning systems, strengthening veterinary services, and promoting vaccination campaigns for livestock. Government and non-governmental organizations should collaborate to provide mobile clinics and veterinary support in remote areas to ensure rapid response to disease outbreaks. Additionally, building resilient livestock systems through disease-resistant breeds and better disease management strategies can help reduce the overall impact of these hazards.

3.6 The impact of geological and hydrometeorological hazards on livelihoods and community resilience in Ethiopia

Enhancing Ethiopia's resilience to geological and hydrometeorological hazards requires a multi-faceted approach, beginning with improved hazard monitoring and preparedness (Vaitla et al., 2012). Existing early warning systems for seismic, volcanic, and hydrometeorological events are limited, particularly for geological risks that are difficult to predict but can cause severe disruptions (Tofu et al., 2023). Strengthening these systems would allow for timely and accurate forecasts, enabling local communities to take proactive measures. Additionally, high-risk zone mapping should inform land-use planning, guiding infrastructure development and livestock relocation strategies (Yosef et al., 2013). Expanding community-based disaster education programs would further improve preparedness by raising awareness and teaching effective response strategies. Adaptive livestock management is another critical pillar of resilience (Ogato, 2013). Promoting drought-resistant livestock breeds can help mitigate the impacts of extreme weather events, as these breeds are better suited to survive in conditions of water and pasture scarcity (Mulugeta, 2023). Developing contingency plans for livestock relocation and emergency feeding during droughts or floods is essential to minimize losses (Habte et al., 2022). These plans must be region-specific and involve local communities to ensure practicality. Expanding veterinary services in hazard-prone areas is also crucial, as post-disaster disease outbreaks can significantly increase livestock mortality (Mulugeta, 2023).

Investing in resilient infrastructure and financial risk management mechanisms is key to reducing vulnerabilities (Mulugeta, 2023). Constructing earthquake-resistant livestock shelters and protected water sources would ensure the continuity of pastoral livelihoods during crises (Solomon and Belete, 2019). Maintaining critical infrastructure, such as roads and bridges, is vital to ensuring mobility and access to resources. Financial tools such as livestock insurance schemes and emergency funds can provide pastoralists with a safety net during disasters, helping them recover more quickly and reducing economic shocks (Abdela, 2024). Expanding access to these financial instruments would promote long-term sustainability in the face of recurring hazards (IFRC, 2019). Effective policy integration and multi-stakeholder collaboration are essential for comprehensive disaster risk reduction. Geological hazards must be incorporated into broader climate adaptation policies to ensure a holistic approach to risk management (Bachewe et al., 2018). Strengthening institutional coordination between government agencies, NGOs, and local communities will enhance resource efficiency and ensure that interventions are well-aligned. Economic incentives for sustainable rangeland management, including rotational grazing and natural vegetation conservation, can help prevent land degradation and preserve grazing areas, ultimately reducing the pressures that climate change and geological hazards place on pastoralist communities (Sinshaw et al., 2018). This review highpoints that by implementing these strategic measures enhancing hazard monitoring, strengthening adaptive livestock management, improving infrastructure, and fostering multi-stakeholder collaboration—Ethiopia can significantly enhance the resilience of its pastoralist communities and ensure the sustainability of its livestock sector amid increasing environmental uncertainties.

3.7 Climate change interactions with geological and hydrometeorological hazards in Ethiopia

Climate change exacerbates geologic and hydrometeorological hazards in Ethiopia by intensifying the frequency and severity of

extreme weather events, compounding the vulnerabilities of pastoral and agro-pastoral communities Arnold et al., 2018). Prolonged droughts, irregular rainfall patterns, and rising temperatures amplify the effects of geological hazards such as soil erosion, landslides, earthquakes, and volcanic activity, creating a cascading impact on livestock production and food security (Amsalu and Adem, 2009). Increased drought frequency leads to pasture degradation and water scarcity, which, when combined with seismic activities and soil erosion, renders large areas unsuitable for grazing (Bogale and Erena, 2022). This is particularly evident in arid regions like the Somali Region and Oromia's southern zones, where reduced rainfall, coupled with soil erosion, accelerates the loss of soil fertility, further endangering livestock survival (Gezie, 2019). Volcanic activity poses an additional threat as climate-induced changes in rainfall patterns exacerbate water scarcity in regions like Erta Ale and the Afar and Danakil areas, where volcanic ash contamination affects both surface and groundwater supplies (Clarke et al., 2020). During periods of low rainfall, volcanic ash diminishes water quality, leading to dehydration and declining pasture productivity. The long-term presence of ash in the environment stunts vegetation growth and reduces available grazing land, compounding livestock vulnerability (Lumborg et al., 2021; Alemu and Mengistu, 2019).

Rising temperatures further exacerbate seismic activity and water shortages, particularly in the tectonically active Southern Rift (Demissie et al., 2023). As higher temperatures deplete water sources and pastures, pastoralists are forced to migrate longer distances in search of resources, increasing their exposure to hazards such as earthquakes and landslides (Ayele et al., 2016). The interaction between climate extremes, such as droughts and floods, and geological disturbances accelerates soil erosion and disrupts natural water systems, perpetuating a cycle of land degradation and resource depletion (Kebede et al., 2018). Both climate change and geological hazards contribute to land degradation, reducing the land's capacity to support livestock. Landslides and earthquakes, in combination with rising temperatures and shifting precipitation patterns, threaten grazing areas in the Amhara and Tigray regions, where soil erosion depletes arable land for both livestock and crop production (Tadesse and Hailu, 2024). Increasing pressure on natural resources due to climate change and geologic hazards accelerates biodiversity loss and pasture degradation, undermining food security and the resilience of pastoral communities (Abdela, 2024). This review revealed that these interconnected threats highlight the urgent need for comprehensive mitigation and adaptation strategies to safeguard Ethiopia's livestock systems from climate-induced geologic and hydrometeorological hazards.

3.8 Existing adaptation and mitigation strategies

This section reviews the adaptation and mitigation strategies that have been implemented to address the impacts of geological and hydrometeorological hazards on livestock production in Ethiopia. It includes government policies, community-based initiatives, and international support programs aimed at reducing vulnerability and enhancing resilience. The effectiveness and challenges of these strategies are also assessed to provide a comprehensive understanding of current efforts.

3.8.1 Early warning and preparedness

Effective early warning and preparedness mechanisms are critical for mitigating the impacts of geological and hydrometeorological hazards on Ethiopia's livestock sector (Amenu, 2013). However, existing formal early warning systems remain underdeveloped, particularly in rural pastoralist regions (Begna et al., 2024). Seismic and volcanic monitoring infrastructures are concentrated in urban centers, leaving pastoralists vulnerable to sudden natural events such as volcanic eruptions in the Erta Ale region, which threaten grazing lands and water resources (Clarke et al., 2020). The limited reach of Ethiopia's National Meteorological Agency (NMA) weather forecasting further exacerbates the challenge, as communication channels often fail to deliver timely warnings to remote communities (Ogato, 2013). Despite these gaps, pastoralists have long relied on indigenous knowledge to predict and respond to natural hazards. Traditional methods, such as observing shifts in animal behavior, plant cycles, and cloud formations, serve as valuable early warning indicators (Mulugeta, 2023). However, these approaches lack scientific precision and are often reactive rather than proactive (Ogato, 2013). Therefore, an integrated strategy that combines indigenous knowledge with modern technologies, such as remote sensing and mobile-based hazard alerts, is essential for strengthening early warning systems (Tofu et al., 2023). Efforts to enhance preparedness include strengthening monitoring infrastructure and expanding real-time communication channels. For instance, leveraging mobile networks for hazard dissemination can significantly improve pastoralists' ability to respond to threats (Yosef et al., 2013). Additionally, training programs aimed at equipping local leaders with skills to interpret and relay meteorological information can bridge the gap between scientific forecasting and community preparedness (Lumborg et al., 2021). Investing in these systems can reduce livestock losses and improve the overall resilience of Ethiopia's pastoralist communities.

Geospatial data and remote sensing tools play a growing role in identifying geohazard hotspots in Ethiopia. Technologies such as satellite-based rainfall monitoring (e.g., CHIRPS), land cover mapping *via* MODIS, and ground deformation tracking using Sentinel-1 are increasingly employed to enhance early warning systems and support targeted interventions in regions where livestock are highly exposed to geohazards (Wondim, 2016). These tools offer valuable insights into spatial and temporal patterns of risk, enabling more informed decision-making. However, their application in Ethiopia faces several limitations ((Amenu, 2013). These include inadequate technical capacity at local levels, limited internet connectivity in remote areas, and insufficient integration of geospatial data into national and regional planning systems ((Tadesse and Hailu, 2024). Additionally, high-resolution data are often costly or unavailable, and real-time monitoring is constrained by delays in data processing and dissemination. Addressing these challenges is essential to fully leverage the potential of remote sensing for effective geohazard risk management and livestock protection.

3.8.2 Livestock management and diversification

Livestock management and diversification strategies have been central to enhancing the adaptive capacity of Ethiopia's pastoralist sector in the face of climate and geological hazards (Habte et al., 2022). A key adaptation strategy has been the promotion of drought-resistant livestock breeds, such as Boran cattle, which exhibit resilience to extreme temperatures and scarce water availability (Ayele et al., 2020). While the adoption of such breeds is widespread, challenges persist due to limited access to veterinary services, disease outbreaks, and insufficient livestock health monitoring systems (Tofu et al., 2023). For example, during the 2016 drought, the spread of anthrax and foot-and-mouth disease led to significant livestock losses, exacerbated by the unavailability of vaccines and veterinary support in remote areas (Bogale and Erena, 2022). Diversification within the livestock sector is a vital strategy for reducing vulnerability to climatic and environmental hazards (Sinshaw et al., 2018). By maintaining a mix of species such as cattle, goats, sheep, and camels pastoralists can buffer against the adverse effects of droughts, floods, and diseases that tend to impact certain species more severely than others. Camels, for example, have demonstrated higher resilience to prolonged drought conditions compared to cattle, making them an increasingly preferred option in arid and semi-arid regions like Afar and Somali (Yosef et al., 2013). In these areas, communities have begun to incorporate camels and small ruminants into their herds alongside traditional cattle. However, the adoption of livestock diversification is uneven across regions due to barriers such as limited veterinary services, insufficient feed availability, and entrenched cultural preferences. To overcome these challenges and expand successful practices, targeted training on species-specific management, along with improved access to pasture and water resources, is essential (Ogato, 2013). Beyond livestock, alternative livelihoods such as small-scale agriculture, handicrafts, and eco-tourism have emerged as supplementary income sources (Solomon and Belete, 2019). In the Somali region, for example, some pastoralists have transitioned to small-scale horticulture to mitigate the economic shocks of recurrent droughts (Tofu et al., 2023). However, these livelihood diversification efforts are often hindered by inadequate access to land, water, and financial resources (Yosef et al., 2013). Expanding government support in the form of microfinance programs and technical training can enhance the viability of diversified livelihoods, reducing dependency on livestock as the sole source of income.

3.8.3 Policy and institutional support

The Ethiopian government has recognized the urgent need to address climate-induced hazards affecting livestock production through policy interventions (Zegeye, 2018). Strategies such as the National Adaptation Programme of Action (NAPA) and the Climate-Resilient Green Economy (CRGE) initiative underscore the importance of targeted adaptation measures for pastoralist communities (Bogale and Erena, 2022). However, significant challenges remain in implementation due to funding limitations, weak institutional coordination, and inadequate monitoring frameworks (Arnold et al., 2018). A major barrier to effective policy execution is the underfunding of disaster risk reduction programs. While national policies emphasize the importance of improving early warning systems and veterinary services, limited financial resources have hampered their expansion into remote pastoralist areas (Abdela, 2024). Addressing these gaps requires increased investment in adaptive infrastructure, including livestock disease surveillance, water management systems, and community-led resilience programs (Das, 2005). Institutional coordination is another critical issue. The lack of a cohesive framework to align governmental and non-governmental efforts often results in fragmented disaster response strategies (Mengistu, 2011). For instance, during the 2015–2016 drought, inefficiencies in aid distribution arose due to misaligned efforts between federal agencies, regional authorities, and international organizations (Bogale and Erena, 2022). Establishing a centralized coordination mechanism could improve resource allocation and ensure timely interventions.

Additionally, community engagement in policy-making remains limited, leading to the development of strategies that do not fully reflect local needs (Abdela, 2024). Participatory approaches, such as integrating indigenous knowledge into formal decision-making processes, can enhance the relevance and effectiveness of adaptation strategies (Bogale and Erena, 2022). Strengthening local governance structures and fostering community-led initiatives will be essential for ensuring long-term sustainability and resilience within Ethiopia's livestock sector. The bar chart given below presents analysis for the distribution of disaster response strategies across different hazard types, distinguishing between climate-related and geological hazard strategies (Mengistu, 2011). The data reveal a clear divergence in focus: responses to droughts and floods are predominantly climate-related, making up over 60% of the interventions. In contrast, strategies addressing earthquakes, volcanic eruptions, and landslides are overwhelmingly geological, with minimal incorporation of climate-related measures. Interestingly, landslides exhibit a blend of both approaches, though geological hazard strategies remain the dominant response mechanism. This pattern suggests a sectoral specialization in disaster management, where climate-related interventions are tailored to hydrometeorological hazards, while geological response frameworks prioritize seismic and volcanic risks. The findings highlight the need for a more integrated disaster response framework that accounts for the complex interactions between climate and geological hazards, ultimately enhancing resilience in vulnerable regions.

While hazard mapping and early warning systems are promoted in national strategies, implementation remains limited in practice (Arnold et al., 2018). In high-risk regions like the Rift Valley, constraints such as inadequate infrastructure, lack of local technical capacity, and limited coordination among stakeholders hinder policy execution (Bogale and Erena, 2022). This review highlights the need for context-specific policy tools and stronger support from both government and international actors for effective field-level application (Figure 12).

4 Discussion

In this section, we synthesize the existing knowledge on the geological and hydrometeorological hazards that significantly affect livestock production in Ethiopia. These hazards, such as droughts, floods, and seismic events, have wide-reaching

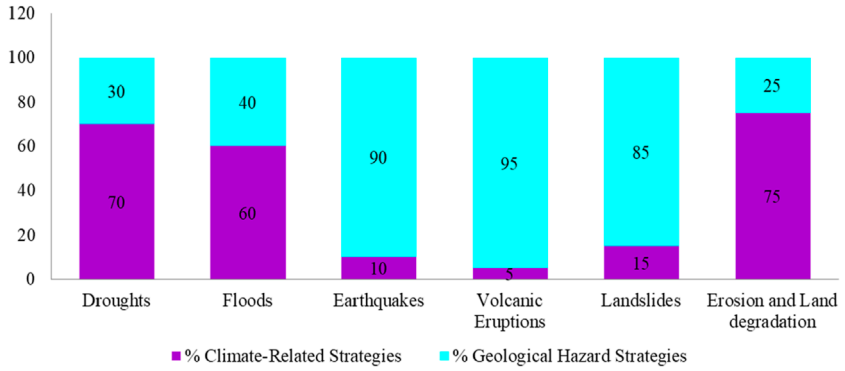

FIGURE 12
Analysis on focus of disaster response frameworks on different hazard types.

implications for livestock health, productivity, and market systems. Climate change has exacerbated these hazards, amplifying their frequency and severity, which in turn threatens the stability of the agricultural sector. This section outlines the key impacts, adaptation strategies, and mitigation measures proposed in the literature, highlighting gaps in research and knowledge, and offering a foundation for future studies and policy recommendations aimed at enhancing the resilience of Ethiopia's livestock systems.

4.1 Major geological and hydrometeorological hazards affecting livestock production in Ethiopia

Ethiopia's livestock sector is highly susceptible to both geological and hydrometeorological hazards, which threaten animal health, productivity, and market stability (Amenu, 2013; Asresie et al., 2015; Bachewe et al., 2018). Geological hazards such as volcanic eruptions, earthquakes, and landslides, although less frequent than climatic hazards, have significant localized impacts (Solomon and Belete, 2019). Volcanic eruptions, such as the 2005–2006 Mount Erta Ale eruption, have contaminated water sources and grazing lands, leading to increased livestock mortality and reduced productivity (Clarke et al., 2020; Tierz et al., 2020; Vye-Brown et al., 2016). Similarly, earthquakes and landslides disrupt critical infrastructure, including water supply systems, animal shelters, and pasturelands, exacerbating the challenges faced by livestock-dependent communities (Ayele, 2017; Ayele et al., 2016; Fentahun et al., 2021). However, empirical data on these hazards' direct effects on livestock are sparse, making risk assessment and mitigation efforts challenging. Hydrometeorological hazards, particularly droughts and floods, are more extensively documented and pose the most significant threats to livestock production (Habte et al., 2022; Kebede et al., 2018; Lumborg et al., 2021). Recurrent droughts lead to forage scarcity, water shortages, and increased disease outbreaks due to weakened animal immunity (Abdela, 2024; Bogale and Erena, 2022; Habte et al., 2022). For example, the 2015–2016 El Niño-induced droughts caused significant livestock losses, with reports indicating that over one million animals perished, leading to severe economic and food security crises (Mulugeta, 2023; Bogale and Erena, 2022). Conversely, excessive rainfall and subsequent flooding, particularly in lowland pastoral regions, increase the spread of waterborne diseases, damage grazing lands, and displace livestock herds, further exacerbating vulnerabilities (Demissie et al., 2021; Dixit and Balasubramanian, 2006; Ogato et al., 2020). This review thus highlights the urgent need for integrated mitigation and adaptation strategies to enhance the resilience of Ethiopia's livestock sector against both geological and hydrometeorological hazards.

4.2 Impacts of geological and hydrometeorological hazards on livestock productivity, health, and market systems

Geological and hydrometeorological hazards significantly undermine livestock productivity, health, and market stability in Ethiopia (EGS, 2019; Ibrahim et al., 2021; World Bank, 2018). Livestock productivity is often compromised by these hazards through reduced milk yields, diminished weight gains, and increased mortality rates, leading to severe declines in household incomes and national economic performance (Bogale and Erena, 2022; Yosef et al., 2013). During prolonged droughts, pastoralists face devastating livestock losses, frequently resorting to distress sales at depressed prices due to oversupplied markets (Abdela, 2024; Habte et al., 2022; Mulugeta, 2023). This market saturation drives price volatility, weakens purchasing power, and deepens food insecurity among already vulnerable communities (Solomon and Belete, 2019). Livestock health is further jeopardized as climate-induced stress increases susceptibility to infectious diseases such as peste des petits ruminants (PPR), foot-and-mouth disease (FMD), and Rift Valley fever (RVF) (Ibrahim et al., 2021; Ikegami and Makino, 2011; Nanyingi et al., 2015). Notably, heavy rainfall and flooding have triggered RVF outbreaks in lowland regions, threatening both animal and human health due to the zoonotic nature of the virus (Demissie et al., 2023). Similarly, the degradation of grazing lands from soil erosion and recurrent droughts forces

animals to rely on poor-quality forage, resulting in nutritional deficiencies and further reductions in productivity (Teku et al., 2024a). Market systems are equally destabilized by these hazards. Droughts reduce the supply of healthy animals to markets, while geological events such as landslides, earthquakes, and volcanic eruptions can disrupt critical infrastructure including roads, livestock corridors, and market centers, limiting trade and access to services (Habte et al., 2022; Mulugeta, 2023; Bogale and Erena, 2022). The 2005–2006 Mount Erta Ale eruption, for example, rendered nearby grazing areas and water points unusable, indirectly affecting market participation and livestock trade (Solomon and Belete, 2019). Disease outbreaks often lead to movement restrictions, which hinder market access and export flows, weakening Ethiopia's livestock-based foreign exchange earnings (Clarke et al., 2020). Overall, this review emphasizes that both geological and hydrometeorological hazards exert compound pressures on Ethiopia's livestock sector by deteriorating productivity, intensifying health risks, and destabilizing market systems. Addressing these impacts requires a holistic understanding of the interconnected nature of environmental shocks and livestock-based livelihoods.

4.3 Exacerbation of geological and hydrometeorological hazards by climate change

Climate change intensifies the frequency, severity, and complexity of both geological and hydrometeorological hazards, thereby compounding their adverse effects on livestock production systems in Ethiopia (Alemu and Mengistu, 2019; Amsalu and Adem, 2009; Bogale and Erena, 2022). Rising temperatures and increasingly erratic rainfall patterns are altering pasture growth cycles, extending the duration and intensity of droughts, and contributing to chronic water scarcity (Habte et al., 2022). Since the 1960s, Ethiopia has experienced an average temperature increase of approximately 1.3°C, with future projections indicating continued warming (Teku and Eshetu, 2024). This trend accelerates land degradation and desertification, reducing pasture availability and forcing pastoralist communities to migrate further in search of feed and water. Such movements heighten resource-based competition and intercommunal tensions, undermining both social cohesion and livelihood stability (Abdela, 2024; Ayele et al., 2020). Hydrometeorological hazards, including prolonged droughts followed by intense rainfall, are becoming more frequent due to climate variability. These events often lead to flash floods and, in topographically vulnerable areas, trigger landslides that destroy grazing areas, animal shelters, and critical infrastructure (Dixit and Balasubramanian, 2006; Ogato et al., 2020; Tadesse et al., 2024). Although geological hazards such as volcanic activity and earthquakes are not directly caused by climate change, the associated environmental shifts such as increased rainfall and soil saturation can exacerbate secondary geological impacts like landslides (World Bank, 2018). These compound risks disrupt livestock production cycles, damage rangeland ecosystems, and hinder market access (Solomon and Belete, 2019). Furthermore, the increasing unpredictability of climate patterns challenges the effectiveness of traditional coping mechanisms (Tofu et al., 2023). Frequent and overlapping shocks give livestock insufficient time to recover, weakening animal health and productivity (Zegeye, 2018). As animals experience more stress without adequate respite, susceptibility to disease and mortality rates rise, eroding household resilience (Tofu et al., 2023). This review thus highlights the urgent need for integrated risk management strategies that address the interlinkages between climate change and hazard dynamics, while strengthening livestock adaptation and recovery capacity.

4.4 Adaptation and mitigation strategies: implementation and effectiveness

Ethiopia has implemented various adaptation and mitigation strategies to enhance the resilience of its livestock sector in response to climate variability and extreme events (Arnold et al., 2018; Yosef et al., 2013). These strategies, however, vary in effectiveness due to differences in regional applicability, financial investment, and policy coherence (Abdela, 2024). Climate-smart livestock management practices, such as drought-resistant fodder production, improved rangeland management, and water harvesting techniques, have demonstrated potential in mitigating climate risks (Das, 2005). In drought-prone areas, the establishment of fodder banks and rotational grazing systems has enhanced feed availability during dry seasons (Habte et al., 2022; Mulugeta, 2023). However, widespread adoption remains a challenge due to limited financial and technical support for pastoralists (Tofu et al., 2023). Early warning systems have been developed to improve disaster preparedness, particularly for droughts and floods (Ogato et al., 2020). The National Meteorological Agency (NMA) and the Disaster Risk Management Commission (DRMC) provide climate forecasts and drought alerts, allowing pastoralists to make informed decisions about livestock movements and resource allocation (Wondim, 2016). The analysis in given Figure 13 compares the effectiveness of indigenous knowledge and formal early warning systems for pastoralists in Ethiopia. It highlights that indigenous knowledge is perceived as significantly more effective (75%) than formal warning systems (25%) in providing early warnings for hazards. This suggests that local, experience-based forecasting methods play a crucial role in climate adaptation and risk management for livestock-dependent communities. The figure underscores the need for integrating indigenous knowledge with formal systems to enhance resilience against geological and hydrometeorological hazards affecting livestock production in Ethiopia. Despite these advancements, the integration of indigenous knowledge remains limited, reducing the accessibility and practical utility of these systems for many pastoralist communities. Moreover, Ethiopia's efforts in livestock risk management have included the introduction of Index-Based Livestock Insurance (IBLI), which offers financial protection against drought-related losses.

This initiative, piloted in the Afar and Somali regions, provides payouts based on satellite-derived vegetation indices rather than direct livestock mortality (Ogato, 2013). While promising, its coverage remains insufficient, and many pastoralists either lack awareness or the financial means to participate in the scheme (Mulugeta, 2023). Rangeland and water resource management initiatives have also played a role in enhancing

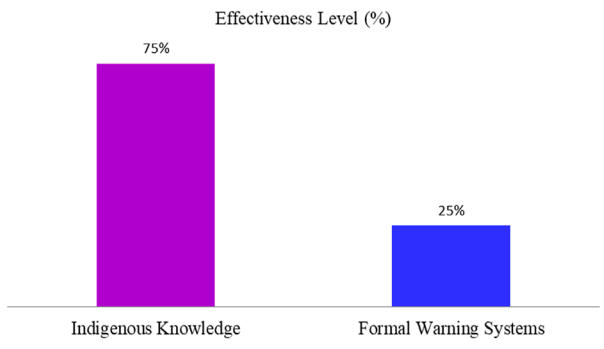

FIGURE 13
Analysis on the effectiveness of indigenous knowledge and formal early warning systems.

livestock resilience (Tofu et al., 2023). Efforts to rehabilitate degraded rangelands through reseeding, soil conservation, and afforestation have improved pasture availability in some regions (Yosef et al., 2013). Additionally, water resource development projects, such as borehole drilling and small-scale irrigation schemes, have increased water accessibility for both livestock and human consumption (Abraha et al., 2022). However, governance challenges and inadequate maintenance have hindered the long-term sustainability of these interventions (Abdela, 2024; Das, 2005). On the policy front, Ethiopia's frameworks, including the Climate Resilient Green Economy (CRGE) strategy and the National Disaster Risk Management Policy, provide a foundation for climate adaptation (Mengistu, 2011; Battistelli et al., 2022). Nonetheless, weak coordination among government agencies, NGOs, and local communities has led to fragmented implementation (Bachewe et al., 2018). Strengthening institutional collaboration and ensuring active local participation in decision-making processes are critical for improving policy effectiveness and fostering long-term resilience in the livestock sector (Ogato, 2013). The pie chart given below illustrates the analysis on key policy implementation challenges in livestock disaster management in Ethiopia (Figure 14). It identifies four major barriers: weak land-use policy enforcement (30%), lack of financial mechanisms (25%), coordination gaps (25%), and limited institutional capacity (20%). The distribution suggests that ineffective land-use policies are the most significant challenge, followed by financial constraints and coordination issues, while institutional limitations also play a role. Addressing these barriers is essential for improving disaster resilience and sustainability in livestock management.

5 Future research directions

Future research on Ethiopia's livestock sector should address significant knowledge gaps related to the impacts of geological hazards, such as volcanic eruptions, earthquakes, and landslides, which remain largely undocumented (World Bank, 2018). While the effects of droughts and floods on livestock are well studied, limited empirical data exist on how these hazards disrupt livestock health, productivity, and pastoralist livelihoods. For example, the 2017 Erta Ale volcanic eruption in the Afar region damaged grazing lands and water sources, yet its precise impact on livestock remains unclear (Clarke et al., 2020). Earthquakes, though rare, can displace herders and disrupt critical infrastructure, indirectly leading to livestock losses (Lemenkova, 2022). Future studies should quantify these direct and indirect effects by integrating field data with hazard modeling systems. Advanced methods, such as remote sensing and satellite imaging, can be employed to monitor pastureland degradation, track infrastructure damage, and assess the cascading impacts of geological hazards on livestock production (Alemu et al., 2018). Additionally, understanding how these hazards interact with climate-related events, such as droughts or floods, is crucial for developing more comprehensive disaster preparedness and response strategies.

Another critical area of research is evaluating the cost-effectiveness of existing disaster response and livestock adaptation strategies. While Ethiopia has implemented various measures, including early warning systems and drought-resistant livestock breeds, there is limited research on their economic viability and long-term benefits (Tierz et al., 2020). Investments in emergency shelters or livestock insurance, for instance, may have high initial costs, but their potential to reduce livestock losses and recovery times needs further assessment. Future studies should conduct cost-benefit analyses to determine the most efficient allocation of resources and identify strategies that offer the highest return on investment (Zegeye, 2018). Additionally, institutional frameworks supporting disaster response and adaptation require evaluation, particularly in terms of coordination between government agencies, NGOs, and local communities (Alemu and Mengistu, 2019). Research should assess existing mechanisms, identify gaps, and propose improvements to ensure timely and effective support for pastoralists.

Innovative and cost-effective livestock management strategies also warrant further exploration. Approaches such as mobile veterinary services, community-based rangeland management, and improved insurance schemes could enhance disaster resilience while fostering long-term sustainability (Zegeye, 2018). Evaluating the economic feasibility and scalability of these initiatives across Ethiopia's diverse agro-ecological zones would provide valuable insights into their broader implementation (Clarke et al., 2020). Furthermore, the role of government policies and financial mechanisms, including insurance, emergency funds, and subsidies, should be critically examined. While Ethiopia's National Disaster Risk Management Policy acknowledges the importance of livestock resilience, there is little empirical data on financial allocations and policy effectiveness in practice (Tierz et al., 2020). Research assessing these financial instruments could inform improvements in disaster risk management, ensuring that pastoralist communities receive the necessary support during and after crises. In conclusion, future research should prioritize the quantitative assessment of livestock losses due to geological hazards, cost-effectiveness evaluations of adaptation measures, and the development of integrated disaster response strategies. By addressing these gaps, researchers can provide a stronger evidence base for policy development, enhance disaster preparedness, and improve the resilience of Ethiopia's livestock sector in the face of multiple hazards.

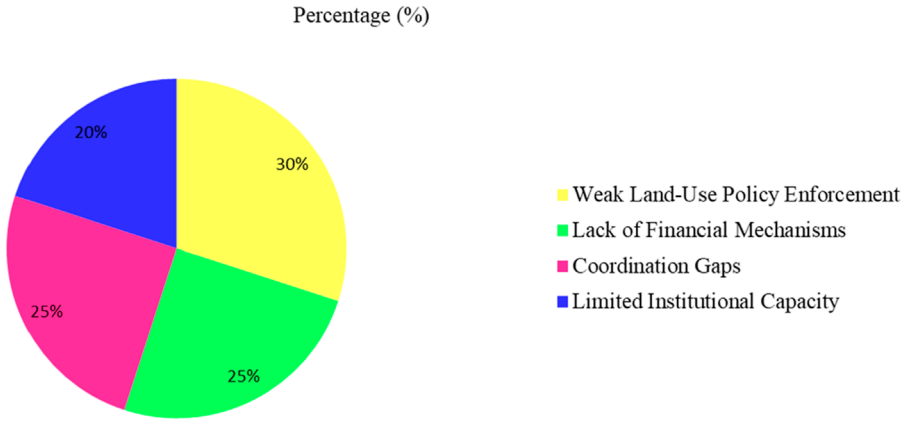

FIGURE 14
Analysis on policy implementation challenges in livestock disaster management in Ethiopia.

6 Conclusion and recommendations

This section concludes the review by summarizing the key findings and providing a set of actionable recommendations based on the discussions of geological and hydrometeorological hazards and their impacts on livestock production in Ethiopia. The following subsections will focus on synthesizing the critical insights drawn from the literature, offering policy and practical recommendations, and identifying areas for future research. By addressing the current gaps and challenges in managing these hazards, the recommendations aim to support more resilient livestock systems, improve adaptation and mitigation strategies, and guide future efforts in enhancing the sector's sustainability and productivity.

6.1 Conclusion

Ethiopia's livestock sector is highly vulnerable to various geological and hydrometeorological hazards, including droughts, floods, volcanic eruptions, earthquakes, and landslides. Among these, droughts and floods are the most extensively documented, with well-established links to livestock mortality, reduced productivity, and pasture degradation. However, the impact of geological hazards such as earthquakes and volcanic eruptions remains inadequately studied, limiting comprehensive risk assessment and response strategies. These hazards have severe implications for livestock productivity, health, and market systems. Droughts and erratic rainfall patterns reduce water availability and pasture quality, leading to malnutrition, disease outbreaks, and lower reproductive rates in livestock. Floods exacerbate waterborne diseases and disrupt local and regional livestock markets by destroying infrastructure and limiting mobility. Additionally, prolonged exposure to environmental stressors weakens livestock immune systems, increasing mortality rates and reducing overall productivity. Climate change further intensifies these challenges by increasing the frequency and severity of hydrometeorological and geological hazards. Rising temperatures and shifting precipitation patterns contribute to prolonged dry spells, sudden heavy rainfall events, and increasing desertification. These changes heighten the vulnerability of Ethiopia's pastoral communities, making traditional coping mechanisms less effective and increasing the reliance on external interventions.

Despite the growing risks, adaptation and mitigation strategies remain fragmented and insufficient. While efforts such as early warning systems, veterinary services, and climate-resilient pasture management exist, they are often underfunded and lack integration across government agencies and local communities. Moreover, disaster risk reduction policies do not adequately address the compound effects of multiple hazards, leaving gaps in preparedness and response efforts. A coordinated, multi-stakeholder approach is essential to enhance Ethiopia's livestock sector resilience. Strengthening collaboration between government agencies, non-governmental organizations, and local pastoralists is critical for improving policy integration and response effectiveness. Additionally, indigenous knowledge systems which have long played a crucial role in managing environmental hazards must be better incorporated into national disaster planning. Combining traditional knowledge with modern science can improve early warning systems, grazing management, and drought coping strategies, ultimately supporting a more sustainable and resilient livestock sector in Ethiopia.

6.2 Recommendations

Ethiopia must adopt a comprehensive and multi-dimensional approach to enhance its resilience to geological and hydrometeorological hazards, particularly those impacting livestock production. A key priority is the strengthening of hazard monitoring systems. Current monitoring efforts for seismic, volcanic, and hydrometeorological events remain inadequate, especially in the face of unpredictable geological risks. Enhancing early warning systems for these hazards, alongside investment in mapping high-risk zones, would facilitate better land-use planning, ensuring that infrastructure development and livestock relocation during crises are well-coordinated. In parallel, expanding community-based disaster education programs is essential to raise awareness

and equip local populations with strategies for effective disaster response. These programs should provide training on emergency preparedness, response, and recovery, empowering pastoralists to take timely action during hazardous events. Adaptive livestock management should also be prioritized as a core strategy for reducing environmental stresses. Promoting the use of drought-resistant livestock breeds can significantly improve survival rates during extreme weather events. Region-specific contingency plans for livestock relocation and emergency feeding are critical to minimize losses, particularly in areas prone to recurring droughts or floods. Additionally, expanding veterinary services in hazard-prone areas is vital to prevent disease outbreaks that may follow disasters, improving overall livestock health and reducing post-disaster mortality rates.

Infrastructure resilience is another critical area for investment. Constructing earthquake-resistant livestock shelters, ensuring access to reliable water sources, and maintaining roads and bridges are all vital to safeguarding pastoralist livelihoods. These infrastructure improvements would help mitigate the impact of seismic events and floods, providing greater access to grazing lands and emergency resources. Financial risk management mechanisms, such as livestock insurance schemes and emergency funds, would offer a safety net for vulnerable pastoralists, enabling faster recovery from climate-induced losses and reducing economic vulnerability. To further strengthen resilience, a coordinated approach across sectors is essential. The integration of geological hazards into broader climate adaptation policies will enable more holistic risk management. Strengthening coordination among government agencies, NGOs, and pastoralist communities will ensure that resources are allocated efficiently and that adaptation measures are implemented effectively. Incentives for sustainable rangeland management, such as promoting rotational grazing and vegetation conservation, should be incorporated into policy frameworks. These measures would reduce land degradation, supporting long-term ecosystem stability and ensuring sustainable livestock production systems. In conclusion, Ethiopia's livestock sector faces growing challenges from both climate change and environmental hazards. Addressing these threats requires a coordinated, strategic approach that incorporates enhanced hazard monitoring, adaptive livestock management, resilient infrastructure, and effective collaboration across all relevant sectors. By implementing these recommendations, Ethiopia can improve the resilience of its pastoral communities and secure the long-term sustainability of its livestock sector in an increasingly unpredictable climate.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

DT Conceptualization, Formal Analysis, Investigation, Methodology, Software, Writing – original draft, Writing – review and editing. TD: Conceptualization, Resources, Validation, Writing – original draft.

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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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