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Uncovering the drivers, impacts, and urgent solutions to soil erosion in the Ethiopian Highlands: a global perspective on local challenges

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Soil erosion in the Ethiopian Highlands is a critical environmental challenge, driven by both natural and anthropogenic factors such as deforestation, overgrazing, unsustainable agricultural practices, and climatic variability. Addressing this issue is essential for safeguarding the region's agricultural productivity, biodiversity, and socio-economic stability. This review aims to synthesize and evaluate existing research on the extent, impacts, and mitigation strategies of soil erosion across the Ethiopian Highlands, with a focus on informing sustainable land management practices and policy interventions. The review draws on findings from 129 peer-reviewed studies and reports, providing a comprehensive national-scale assessment of soil erosion. The selected literature encompasses empirical field studies, remote sensing analyses, and policy evaluations. The reviewed literature highlights severe soil degradation, with erosion rates in some areas exceeding 200 tonnes per hectare annually, resulting in the loss of over 1.5 billion tonnes of topsoil each year. This degradation reduces agricultural productivity by 5%–10% annually and causes economic losses exceeding $1 billion, approximately 2% of Ethiopia's GDP. The impacts of soil erosion extend to water quality, biodiversity, and rural livelihoods. Mitigation strategies such as terracing, stone bunds, and agroforestry have demonstrated potential to reduce soil loss by up to 60%, stabilize slopes, and enhance soil organic matter. This review underscores the urgency of integrated and scalable approaches to combat soil erosion, combining sustainable land management practices, supportive policy frameworks, and active community engagement.

KEYWORDS

soil erosion, Ethiopian Highlands, natural and anthropogenic causes, socio-economic impacts, sustainable solutions, policy and practice implications

1 Introduction

Soil is an indispensable element of the Earth's ecosystem, playing a central role in biogeochemical processes, water cycles, and sustaining human societies through the provision of essential resources and ecosystem services (Huggett, 2023). Globally, soil degradation is a critical issue, as it affects agricultural productivity, ecosystem stability, and climate regulation. According to Smith et al. (2015), soil serves not only as a medium for plant growth but also as a crucial carbon reservoir, thereby regulating atmospheric

greenhouse gases. Approximately 99.7% of human dietary calories are derived from terrestrial sources, underscoring the global importance of soil conservation to sustain food security and human welfare (Degu and Huluka, 2019). It is crucial to recognize that soil degradation in the Ethiopian context carries unique challenges and implications. Agriculture is the backbone of the economy, with more than 85% of the population depending on it for livelihood (Solomon et al., 2024). This makes soil health not only an environmental priority but also a cornerstone of Ethiopia's socio-economic stability. Ethiopian soils have been significantly degraded over the centuries, particularly in the Ethiopian Highlands, which account for 43% of the country's land area and 95% of its cultivated land (Kassa et al., 2022). The degradation of soil in the Ethiopian Highlands directly threatens agricultural productivity, biodiversity, and socio-economic stability. The Ethiopian Highlands experience high rates of soil erosion, exacerbated by steep slopes, deforestation, and intense rainfall (Tadesse and Hailu, 2024). This degradation results in the loss of over one billion tonnes of soil annually, leading to profound economic and environmental consequences (Moisa et al., 2022).

The issue is particularly severe in the Ethiopian Highlands, where natural and anthropogenic factors, including deforestation, overgrazing, and poor agricultural practices, accelerate erosion (Tadesse and Hailu, 2024). These highlands suffer from some of the world's highest erosion rates, with soil losses exceeding 200 tonnes per hectare annually in certain areas (Solomon et al., 2024). Moisa et al. (2022) estimate that soil erosion costs Ethiopia approximately $1.9 billion each year, constituting a 3% reduction in the Agricultural Gross Domestic Product (AGDP). Without effective intervention, projections suggest soil erosion could result in a 10% decrease in Ethiopia's GDP by 2045 (Moges and Bhat, 2018). Moreover, around 50% of the Ethiopian Highlands are erosion-prone, with 14 million hectares significantly degraded and over two million hectares considered beyond restoration (Kassa et al., 2022). These losses severely impact food security and hinder Ethiopia's development objectives. Given the critical importance of the Ethiopian Highlands, addressing soil erosion is imperative to sustaining agricultural productivity, ensuring food security, and supporting long-term economic stability. This highlights the necessity for targeted research to address existing gaps in understanding the causes, impacts, and mitigation of soil erosion in this region. Therefore, this review aims to provide an in-depth, globally contextualized analysis of soil erosion in the Ethiopian Highlands. By examining its causes, impacts, and sustainable management practices, this review seeks to deliver actionable insights and recommendations that support mitigation strategies tailored to Ethiopia's unique environmental, socio-economic, and geographic conditions. Through this comprehensive approach, the review emphasizes the urgency of adopting integrated and community-driven approaches to tackle this pressing environmental challenge. Moreover the review work is amid to answer the following research questions:

1. What are the primary mechanisms and manifestations of soil erosion in the Ethiopian Highlands?
2. What are the primary natural and anthropogenic drivers of soil erosion in the Ethiopian Highlands?
3. How does soil erosion impact agricultural productivity, biodiversity, and socio-economic stability in the Ethiopian Highlands?
4. What sustainable land management practices have been effective in mitigating soil erosion in regions with similar environmental conditions?
5. What policy interventions and community-driven strategies are necessary to address soil erosion and promote long-term land conservation in Ethiopia?

2 Methodology

2.1 Study area

The Ethiopian Highlands, often referred to as the "Roof of Africa," are a mountainous region covering much of central and northern Ethiopia, with elevations ranging from 1,500 to over 4,500 m above sea level (Figure 1). These highlands feature rugged terrains, deep valleys, and fertile plateaus supporting diverse ecosystems and a dense rural population dependent on subsistence agriculture. The climate in this region is characterized by mean annual temperatures ranging from 10°C to 25°C, with average annual rainfall varying between 500 and 2,000 mm. However, rainfall patterns exhibit significant inter-annual variability, which is crucial in understanding the region's vulnerability to soil erosion (National Meteorology Agency, 2023). Soil erosion in the Ethiopian Highlands is influenced by several macro factors, including soil type, land cover, and precipitation. The dominant soil types in this region are predominantly Nitisols and Andosols, which are fertile but prone to erosion when poorly managed. The land cover is a mix of agricultural land, forested areas, and grasslands, with deforestation and land conversion for agriculture exacerbating erosion. In terms of precipitation, the region experiences a bimodal rainfall pattern, with the main rainy season occurring between June and September, and a lesser rainy season from March to May. The high variability in rainfall depth and frequency increases the susceptibility of the region to both water and wind erosion during the wet and dry periods (National Meteorology Agency, 2023).

These environmental dynamics, coupled with socio-economic pressures such as population growth and agricultural intensification, make the Ethiopian Highlands one of the most significant and vulnerable regions in Africa to soil erosion. The interaction between soil properties, land cover changes, and precipitation patterns highlights the need for comprehensive land management strategies to address soil erosion in this critical area. Management history in the Ethiopian Highlands reflects a complex interaction between traditional practices and modern interventions. Indigenous practices such as terracing and agroforestry have been employed for centuries, but population growth, land pressure, and inadequate policy enforcement have diminished their effectiveness. In recent decades, government-led programs like the Sustainable Land Management Program (SLMP) have aimed to restore degraded lands, though challenges remain in scaling these efforts sustainably (Sustainable Land Management Program, 2021).

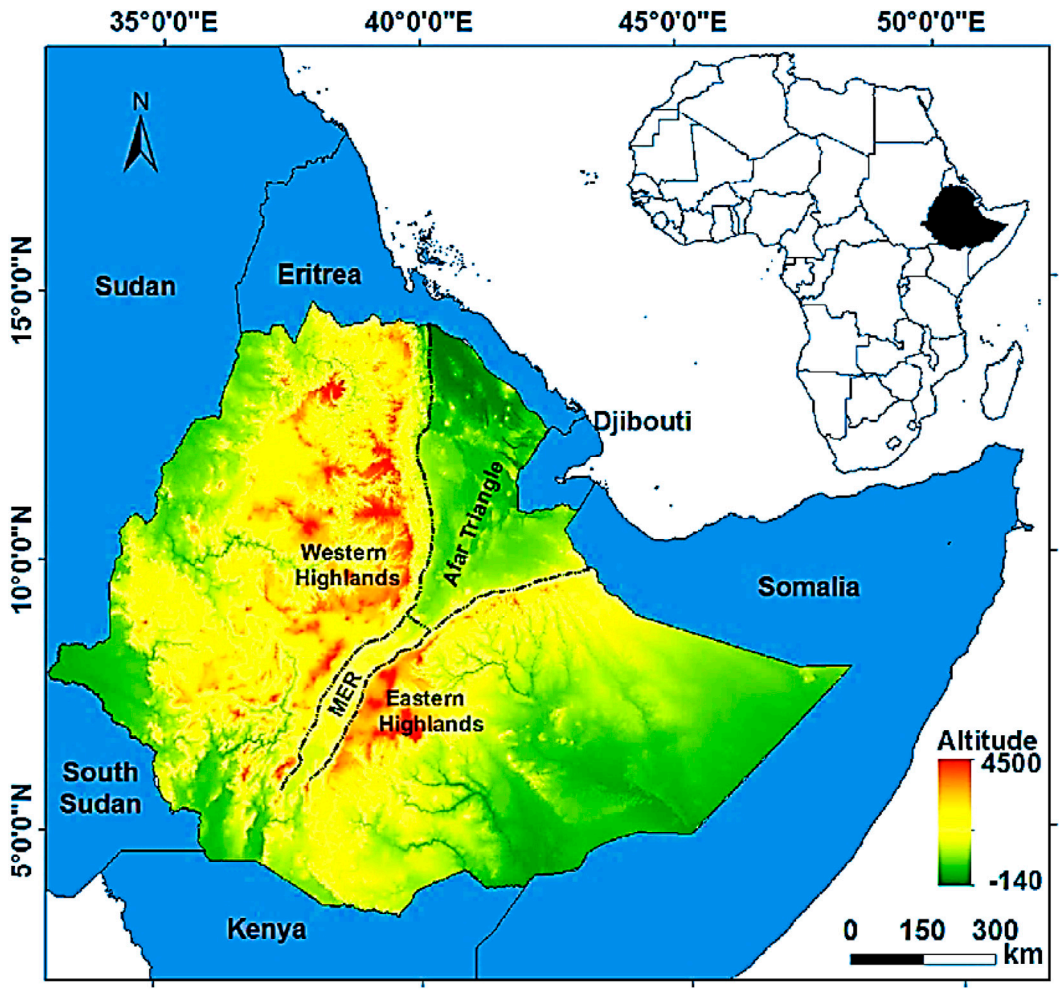

FIGURE 1
Geographic Range and Elevation Profile of the Ethiopian (Hailu et al., 2015).

2.2 Research design

This review employs a narrative research design to synthesize and interpret existing literature on the drivers, impacts, and solutions to soil erosion in the Ethiopian Highlands, situated within a global perspective. The choice of a narrative approach is purposeful; it allows for a flexible, in-depth exploration of soil erosion as a complex, multidimensional challenge. Unlike systematic reviews, which are best suited to narrowly defined questions, a narrative review accommodates interdisciplinary dimensions, facilitating a holistic analysis of environmental, socio-economic, and policy interactions that influence soil erosion in the Ethiopian Highlands. Systematic reviews and meta-analyses were excluded to maintain the focus on integrative and narrative synthesis. These methods, while rigorous, are less suited for exploring the nuanced interplay of diverse factors environmental, social, and policy that characterize soil erosion in Ethiopia. This choice allows for a broader, more contextually relevant analysis.

The initial search identified 696 studies using multiple academic databases, including Google Scholar, PubMed, ScienceDirect, and JSTOR. To refine the results, clear inclusion and exclusion criteria were applied. Inclusion criteria required studies to address soil erosion types, drivers, impacts, or mitigation strategies in the Ethiopian Highlands, with a publication timeframe between 2015 and 2024. Articles not geographically relevant to the Ethiopian Highlands or narrowly focused on technical aspects outside the broader socio-environmental context were excluded. Gray literature was particularly emphasized due to its ability to capture practical and region-specific insights often absent in peer-reviewed research. Government reports, NGO publications, and policy briefs provided essential perspectives on soil erosion's socio-economic dimensions and the efficacy of local interventions. This inclusion ensures a balanced and comprehensive understanding, aligning with the unique challenges faced in the Ethiopian Highlands. After a full-text review, 129 studies were included for analysis (Figure 2). Data extraction was conducted manually, with systematic documentation of each source's type, methods, findings, and recommendations. Quality assessments were qualitative, focusing on methodological rigor, data transparency, and alignment with the study's objectives. For gray literature, additional criteria such as

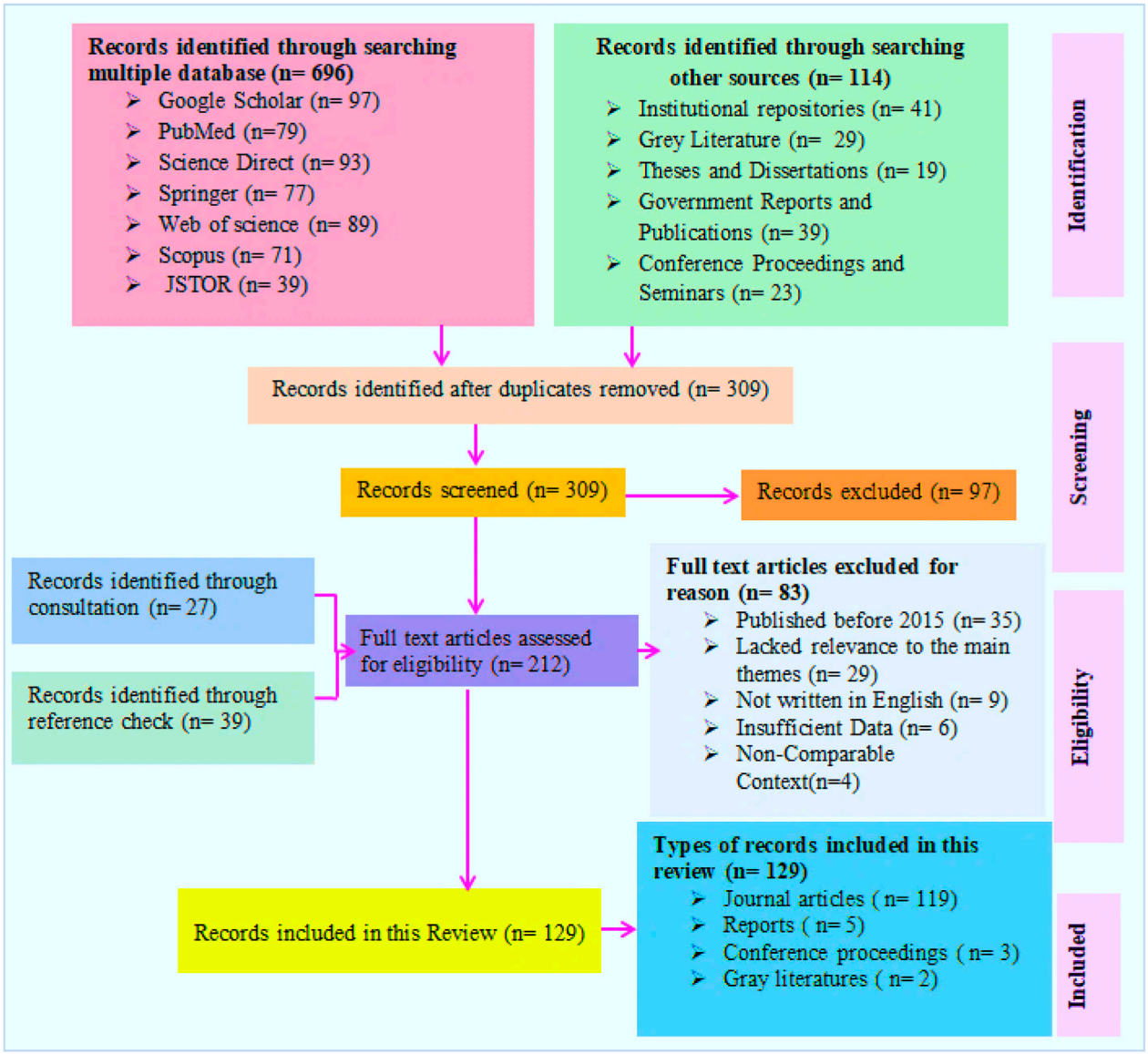

FIGURE 2
Flow diagram of the selection process of included records.

author credibility, organizational affiliation, and publication date were applied to ensure reliability. Relevant studies were organized into six thematic categories aligned with the review's objectives: (1) Types and forms of soil erosion, (2) Contributing factors, (3) Environmental and socio-economic impacts, (4) Sustainable solutions, (5) Policy implications, and (6) Case studies.

3 Results and discussion

3.1 Types of erosion

This section presents the primary mechanisms responsible for erosion in the Ethiopian Highlands, emphasizing their environmental and socio-economic impacts.

3.1.1 Water erosion

Water erosion is a severe issue in the Ethiopian Highlands, characterized by its impact on landscapes and agriculture. In this region, sheet erosion on cultivated hillsides and gully formation in degraded areas are the primary manifestations. Quantitative data indicate erosion rates can reach up to 60 tonnes per hectare per year, significantly higher than the global average of 16 tonnes per hectare per year (Mhiret et al., 2019). Comparisons with other highland regions, such as the Andean Highlands, where average rates are around 30 tonnes per hectare per year (Tenorio et al., 2018), highlight the severity of the problem in Ethiopia. Water erosion impacts are profound, reducing soil fertility and threatening food security. For example, crop yields have decreased by 40% over the past 30 years due to soil loss (Haregeweyn et al., 2015). Sedimentation in rivers degrades water quality, with sediment

loads increasing by up to 30% during the rainy season (Buraka et al., 2024). Water erosion in the Ethiopian Highlands is the most prevalent and impactful type, significantly degrading soil quality and agricultural productivity. Addressing this requires scaling up effective mitigation measures like terracing and reforestation. Mitigation strategies, such as terracing and cover crops, have proven effective. For instance, terracing can reduce soil loss by up to 80% (Debie et al., 2018).

3.1.2 Wind erosion

Wind erosion is significant in the arid and semi-arid regions of the Ethiopian Highlands, where vegetation is sparse. Quantitative studies show wind erosion rates can exceed 10 tonnes per hectare per year (Fenta et al., 2020), higher than regions like the Sahel in West Africa (6 tonnes per hectare per year) (Biyensa et al., 2015). Wind erosion is assessed using dust monitoring stations and wind tunnel experiments. During strong wind events, soil particles can be transported over 100°km (Fenta et al., 2020). Wind erosion's impacts are both environmental and socio-economic, including food insecurity and respiratory issues. Mitigation measures such as vegetative cover and windbreaks have reduced erosion by up to 70% (Biyensa et al., 2015). Wind erosion's prevalence in the Ethiopian Highlands highlights the need for vegetation restoration and strategic use of windbreaks to mitigate its impacts.

3.1.3 Gravitational erosion

Gravitational erosion, including landslides and debris flows, is prevalent in the steep terrains of the Ethiopian Highlands. Landslides displace up to 100,000 cubic meters of soil per event (Tesfa and Woldearegay, 2021). This is comparable to regions like the Himalayas, where landslides also pose significant risks, with similar soil displacement volumes reported (Marc et al., 2019). Studying gravitational erosion involves slope stability analysis, field surveys, and GIS tools. Slope stability analysis in the Ethiopian Highlands indicates that slopes exceeding 30° are highly susceptible to landslides, particularly when soil moisture content exceeds 20% (Mewa and Mengistu, 2022). Field surveys document landslides and debris flows, providing data on their frequency and impact. For example, during the 2019 rainy season, over 50 landslides were recorded, causing significant damage (Tesfa and Woldearegay, 2021). Slope stabilization techniques like terracing and reforestation have proven effective in reducing erosion risk (Mewa and Mengistu, 2022). Gravitational erosion poses significant risks to infrastructure and communities in the Ethiopian Highlands, necessitating robust slope stabilization efforts.

The review underscores that water erosion stands as the most prevalent and destructive form of erosion in the Ethiopian Highlands, driven by intense rainfall and steep terrain. The literature consistently identifies water erosion as the principal factor behind agricultural productivity loss and environmental degradation in the region. To address this, scaling up mitigation strategies such as terracing and reforestation has proven effective, reducing soil loss by up to 80% (Debie et al., 2018). While less extensive, wind erosion remains a significant concern in the drier parts of the highlands, where sparse vegetation exacerbates soil loss. Targeted interventions, including vegetative restoration and windbreak establishment, show potential to reduce wind erosion by as much as 70% (Biyensa et al., 2015). Gravitational erosion, although more localized, poses severe risks in steep and moisture-saturated areas, causing substantial soil displacement and infrastructure damage. The review highlights the critical need for slope stabilization and comprehensive land-use planning to mitigate these localized yet impactful erosion processes.

3.2 Forms of erosion

Forms of erosion describe the physical shapes or features created as a result of erosion processes. Owing to the stage of progress in erosion cycle, the relative depth of the resulting channel and the position of the landscape, the major forms of water erosion include sheet, rill, and gully erosion (Ul Zaman et al., 2018). Figure 3 below illustrates the different forms of erosion as observed in the Ethiopian Highlands. Understanding the different types and forms of soil erosion is critical for identifying the underlying factors that contribute to their occurrence.

3.2.1 Sheet erosion

Sheet erosion is a subtle process where surface runoff removes soil particles uniformly across gentle slopes, often without immediate detection until significant amounts of fertile topsoil are lost (Mhiret et al., 2019). This form of erosion, exacerbated by raindrop impact creating splash erosion, is particularly concerning in regions like the Ethiopian highlands. The combination of steep topography, intense seasonal rainfall, and insufficient vegetation cover accelerates the erosion process (Teku et al., 2024a). In the Ethiopian highlands, inadequate soil conservation practices, deforestation, and unsustainable agriculture further degrade soil structure, reducing its capacity to absorb water and making it more prone to erosion. Recent studies in the Gule Sub-Watershed of northern Ethiopia reported average annual soil losses of 0.098 tha^{-1}, while in the Dapo catchment of the Blue Nile basin, losses were observed at 6.2 t ha^{-1} per year (Grum et al., 2017). Historically, soil erosion in the Ethiopian highlands has led to the loss of billions of tons of topsoil annually, removing tens of thousands of hectares of cropland from production (Nyssen et al., 2015). Compared to other regions with less challenging topography, such as those with typical soil erosion rates of 0.5–2 t ha^{-1} per year, the Ethiopian highlands face a significantly more severe erosion problem (Melese Gezie, 2019), significantly depletes fertile topsoil, reducing agricultural productivity.

Strengthening soil conservation practices is crucial to mitigate these impacts. Effective methods include the construction of terraces, which have been shown to reduce soil erosion by up to 50% in similar regions (Teku et al., 2024b), and the use of check dams, which help to trap water and reduce runoff (Haregeweyn et al., 2015). Agroforestry, involving the integration of trees with crops, has also proven beneficial in preventing soil erosion by improving soil structure and providing windbreaks (Waldén et al., 2024). Additionally, the use of vegetation cover, such as grass strips and cover crops, has been successful in reducing surface runoff and controlling erosion, especially on steeper slopes (Beyene et al., 2023. Implementing these practices at scale, supported by local communities and policy frameworks, can significantly reduce the long-term impacts of soil erosion in the Ethiopian Highlands and improve agricultural sustainability.

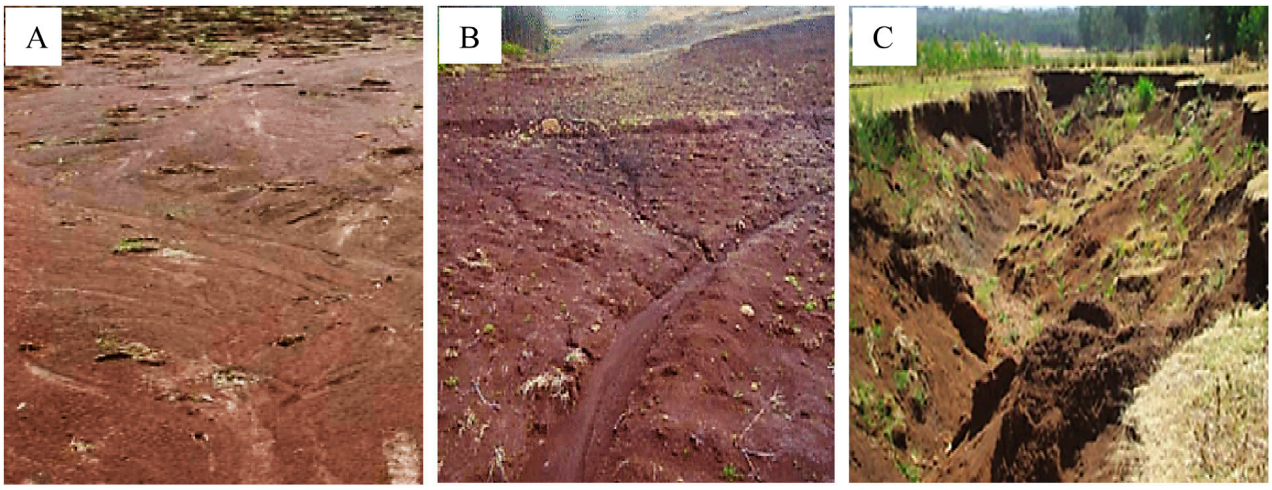

FIGURE 3
Forms of soil erosion in the Ethiopian highlands: sheet **(A)**, Rill **(B)**, Gully **(C)** erosion.

3.2.2 Rill erosion

Rill erosion involves the formation of small channels or depressions on the soil surface due to concentrated water flow, particularly on steep slopes. These channels can deepen and evolve into larger gullies if left unaddressed. The rates of rill erosion in the Ethiopian highlands are alarming, often exceeding global standards. For instance, research in the Ruba Gered watershed of northern Ethiopia reported an annual average soil loss of 3.5 t ha^{-1}, with even higher losses in other sub-watersheds (Zenebe et al., 2023). In the Tigray highlands, the average soil loss rate from sheet and rill erosion was recorded at 31.5 t ha^{-1} yr^{-1}, with specific rates varying across different land uses. Such rates starkly contrast with global soil erosion thresholds, which generally range between 1 and 10 t ha^{-1} yr^{-1} for regions with moderate to intensive land use (Borrelli et al., 2017). The economic impact of rill erosion in Ethiopia is substantial, with annual soil loss costs estimated at around $1.2 billion, and the loss of agricultural productivity due to soil degradation significantly affecting food security (Ghosal and Das Bhattacharya, 2020).

Given the severity of rill erosion, immediate intervention through improved land management strategies is essential. Specific measures, such as the establishment of contour plowing and terracing, have proven to be effective in controlling rill erosion on steep slopes. Contour plowing, where plowing follows the contour of the land, helps to slow down water flow and reduce soil displacement (Beyene et al., 2023). Terracing, which involves creating stepped levels on steep land, has been widely used in the Ethiopian Highlands to reduce the velocity of surface runoff and prevent the formation of rills and gullies (Bedada et al., 2024). In addition, check dams, built across rills to intercept water flow and allow sediment deposition, can effectively prevent further erosion and improve water retention for agricultural use (Haregeweyn et al., 2015). Integrating vegetation cover, including grass strips or cover crops, in areas prone to rill erosion also stabilizes the soil, reducing the erosive power of water and promoting soil fertility (Waldén et al., 2024). These strategies, when tailored to local conditions and supported by government and community engagement, can substantially mitigate rill erosion in the Ethiopian Highlands and reduce its economic and environmental impacts.

3.2.2.1 Gully erosion

Gully erosion, marked by the formation of deep, narrow channels due to concentrated water flow, poses a severe threat to the Ethiopian highlands. It not only exacerbates soil loss but also contributes significantly to sedimentation in water bodies, impacting land management. Studies in the northwestern highlands have reported soil loss rates from gully erosion ranging from 130 to 550 tons per hectare per year, far exceeding the tolerable limit of 18 tons per hectare per year (Addisie and Wassie, 2021). In the Jedeb watershed of the Upper Blue Nile, gully erosion contributed to nearly 32% of the total soil loss, highlighting its significant role in land degradation (Molla and Sisheber, 2017). The economic costs associated with gully erosion are also considerable, with annual losses exceeding $20,000 in affected areas, representing a significant economic burden on local communities (Getnet and Mulu, 2021). In less severely affected regions, the economic costs are generally lower, underscoring the disproportionate impact of gully erosion in the Ethiopian highlands.

The reviewed literature underscores that soil erosion in the Ethiopian Highlands manifests primarily in three forms: sheet, rill, and gully erosion, each contributing significantly to land degradation and agricultural productivity loss. The review reveals that sheet erosion, often subtle yet pervasive, leads to substantial topsoil loss, with studies indicating soil depletion rates as high as 6.2 t ha^{-1} per year in certain catchments. Rill erosion, characterized by channel formation on steep slopes, results in soil losses surpassing global erosion standards, with economic impacts estimated at $1.2 billion annually. However, the review highlights that gully erosion presents the most severe threat, with soil loss rates reaching up to 550 t ha^{-1} annually, significantly exceeding the tolerable threshold of 18 t ha^{-1}. Most of the literature indicates that gully erosion not only accelerates land degradation but also imposes disproportionate economic burdens on affected communities. Effective mitigation strategies such as terracing,

FIGURE 4
Effective soil erosion mitigation strategies in the Ethiopian highlands: Terracing **(A)**, Stone bund **(B)**, Check dam **(C)**, Agroforestry **(D)**, Reforestation **(E)**, Contour farming **(F)**, conservation tillage **(G)**, cover crop **(H)**, grass strip **(I)**.

check dams, and agroforestry emerge as critical interventions, with the review drawing on evidence that their implementation can reduce soil loss by up to 50%. The reviewed studies emphasize the urgency of scaling these interventions to address the compounding impacts of erosion on food security and economic stability in the Ethiopian Highlands.

3.3 Major contributing factors of soil erosion in the ethiopian highlands

3.3.1 Climate variability and rainfall patterns

Soil erosion in the Ethiopian Highlands has become a critical environmental crisis, intensified by extreme climatic factors like intense rainfall, frequent runoff, high winds, and rising temperatures. Rainfall is identified as a primary driver, with intense storms detaching, splashing, and transporting soil particles, significantly reducing the soil's infiltration capacity. Heavy rainfall events, exceeding 200 mm per hour, particularly during peak wet seasons, create swift, powerful runoff that strips soil from hillsides and severely impacts agricultural land (Tullu and Habtegebriel, 2023). Rainfall often surpasses 1,000 mm annually in some parts of the Highlands, which, combined with steep slopes and sparse vegetation, accelerates erosion rates. The Ethiopian climate, influenced by the Inter-Tropical Convergence Zone (ITCZ) and El Niño Southern Oscillation (ENSO), results in erratic wet seasons with rainfall exceeding 500 mm per month (Molla et al., 2019). This intense seasonal rain destabilizes soils, while the prolonged dry seasons degrade soil structure and reduce vegetation, increasing erosion risks during subsequent storms. Projections indicate up to a 20% increase in extreme rainfall events and a 15% reduction in soil moisture by 2050 (Bezu, 2020). Regions impacted by frequent El Niño events experience a 30% increase in erosion rates, further underscoring the need for robust soil conservation measures (Molla et al., 2019). Climate variability, particularly intense rainfall and extreme weather patterns, is a primary driver of soil erosion in the Ethiopian Highlands. The interplay of erratic rainfall, steep slopes, and reduced vegetation exacerbates the problem, with climate change projected to heighten these impacts further. These findings emphasize the urgent need for targeted interventions in land management policies, focusing on water retention structures, reforestation, and sustainable agricultural practices to mitigate erosion and its cascading effects on ecosystems and agriculture.

3.3.2 Deforestation and vegetation loss

The alarming relationship between deforestation and soil erosion in the Ethiopian Highlands marks a critical environmental crisis. Deforestation directly exposes soil to intense erosion from rainfall and runoff, drastically increasing erosion rates. Studies confirm that areas in Tigray with over 30% deforestation experience soil erosion rates as high as 45 tonnes per hectare annually, compared to just 15 tonnes per hectare in forested regions a stark threefold increase linked directly to vegetation loss (Mezgebo et al., 2024). Between 2000 and 2010, Ethiopia lost roughly 1.1 million hectares of forest, driving a 20% surge in soil erosion rates in deforested zones (Tadesse and Hailu, 2024). In Oromia, erosion rates average 35 tonnes per hectare in deforested areas, tripling the rates of stable forested regions. This deforestation results in an annual increase of approximately three million tonnes of eroded soil, undermining agricultural productivity and ecosystem stability (Tsegaye, 2019). Conversely, reforestation and afforestation could reduce erosion by up to 40%, highlighting the urgent need for large-scale, strategic forest management and conservation initiatives (Mesene, 2017). Deforestation is a major contributor to soil erosion in the Ethiopian Highlands, with erosion rates significantly higher in deforested areas. The loss of vegetation cover directly exposes soil to the destructive forces of rainfall and runoff. Addressing deforestation through reforestation and afforestation programs is critical for mitigating soil erosion. Policymakers should prioritize forest conservation and implement large-scale tree-planting initiatives to restore degraded lands and enhance ecosystem resilience.

3.3.3 Land use practices and poor agricultural activities

Agriculture, a cornerstone of livelihoods in the Ethiopian Highlands, is under threat from unsustainable practices driving severe soil erosion. Deep tillage increases soil erosion by 50%, with rates spiking to 30 tonnes per hectare annually in Tigray Highlands, compared to 10 tonnes per hectare in areas using minimal tillage (Abidela Hussein et al., 2019). Overgrazing in regions like the Bale Mountains has driven erosion rates from 20 to 50 tonnes per hectare annually due to vegetation loss and soil compaction (Gashaw, 2015). Cultivation on steep slopes in Sidama results in erosion rates of 40 tonnes per hectare on un-terraced slopes, nearly three times the rate observed with terracing (Muse et al., 2023). Modern shifts to monoculture and cash crop expansion on marginal lands, such as Kaffa, have exacerbated soil degradation, with erosion rates reaching up to 55 tonnes per hectare annually a 70% increase compared to forested areas (Kassa et al., 2015). Urban expansion in Addis Ababa has also intensified soil erosion, amplifying regional environmental vulnerabilities (Mesene, 2017). Unsustainable agricultural practices, including deep tillage, overgrazing, and monocropping, significantly contribute to soil erosion in the Ethiopian Highlands. The impact is compounded by cultivation on steep slopes and urban expansion. Implementing sustainable agricultural practices, such as conservation tillage, agroforestry, and terracing, is essential to mitigate erosion. Policymakers should develop comprehensive land management strategies that integrate soil conservation techniques with community-based interventions to secure agricultural productivity and reduce land degradation.

3.3.4 Population pressure and land fragmentation

In the Ethiopian highlands, rapid population growth and land scarcity drive unsustainable land-use practices as communities attempt to maximize agricultural output from limited resources. This pressure often results in the expansion of marginal lands for farming, inadequate soil conservation measures, and a higher vulnerability to erosion (Cholo et al., 2019). Land fragmentation due to inheritance practices exacerbates this issue, leading to smaller farm sizes that challenge sustainable land management (Zegeye, 2024). As population density increases, farmers are compelled to cultivate marginal lands that are more prone to erosion, which intensifies pressure on natural resources and accelerates soil degradation. Additionally, limited access to agricultural inputs and technology further worsens the situation (Mesene, 2017). This section highlights the critical role of population pressure in land fragmentation and its detrimental effects on soil erosion. The findings suggest that unsustainable land use driven by land scarcity leads to accelerated soil degradation, especially on marginal lands. For policy-making, this emphasizes the urgent need to address population management, land tenure systems, and resource allocation in the region to mitigate soil erosion and promote

sustainable land use. Land reforms and agricultural extension services are key strategies to prevent further degradation.

3.3.5 Topography and slope characteristics of the region

The topography and slope characteristics of the Ethiopian highlands are major contributors to soil erosion (Birhanu et al., 2019). The highlands are characterized by steep slopes, ranging from gentle to very steep gradients, which exacerbate the erosion processes (Wubie and Assen, 2020). According to research by Sime and Abebe (2022), these steep slopes increase the velocity of surface runoff during rainfall, leading to greater soil detachment and transport downslope. Additionally, the region's narrow valleys and ridges concentrate runoff, further intensifying erosion. The combination of high relief and irregular topography creates conditions highly conducive to soil erosion, which significantly impacts agricultural productivity and environmental stability (Ahmedin and Elias, 2022). The steep slopes and irregular topography of the region directly influence soil erosion rates, making soil conservation efforts challenging. The findings underscore the need for topography-specific soil management strategies, such as contour farming and terracing, to address the unique challenges posed by these physical characteristics. Policymakers must prioritize landscape-sensitive interventions to protect highland ecosystems and enhance agricultural productivity.

3.3.6 Geological formations and soil characteristics of the region

The geology and soil profile of the Ethiopian Highlands are contributing to a severe erosion crisis. Fragile, weathered volcanic soils, such as Andosols and Nitisols, erode at alarming rates (Cama et al., 2020). These soils, predominantly found in the region's basalt and andesite compositions, are low in organic matter and structurally weak, making them highly susceptible to erosion. In regions like Sidama, erosion rates can reach 40 tonnes per hectare, double that of areas with more stable soils (Bizunhe, 2023). In the Bale Mountains, erosion rates soar to 50 tonnes per hectare each wet season (Gashaw, 2015), highlighting the extreme vulnerability of these soils. Without targeted conservation efforts, the region's soils will continue to degrade, endangering both the environment and rural livelihoods (Yesuph and Dagnew, 2019). The erosion crisis in the Ethiopian highlands is significantly driven by the region's fragile soils, particularly Andosols and Nitisols. These findings call for soil-specific conservation practices such as organic matter enhancement, erosion control structures, and tailored land management techniques to slow soil degradation. Policy reforms that promote sustainable land practices and investments in soil conservation are critical for maintaining agricultural viability and environmental stability.

3.3.7 Haphazard infrastructure development and soil disturbance

Infrastructure development in the Ethiopian Highlands especially through road construction, urban expansion, and mining has become a major driver of soil erosion. The removal of vegetation and soil compaction due to these activities intensifies erosion rates, especially on steep slopes. For instance, runoff intensifies by up to 200% in areas impacted by infrastructure development (Moges and Bhat, 2018). In road construction, impervious surfaces such as asphalt and concrete channel water flow, leading to erosion rates exceeding 30 tonnes per hectare annually, compared to less than 10 tonnes per hectare in untouched areas (Tiamgne et al., 2022). Mining activities further worsen this situation, with topsoil removal and sediment runoff contaminating ecosystems and increasing erosion by as much as 150% (Moges and Bhat, 2018). Haphazard infrastructure development is exacerbating soil erosion, especially in sensitive areas like steep slopes. The findings suggest that infrastructure planning should integrate environmental impact assessments and erosion control measures to minimize land degradation. Policymakers need to enforce sustainable infrastructure development practices to mitigate erosion and protect ecosystems.

3.3.8 Policy and institutional challenges

Policy and institutional challenges in the Ethiopian highlands significantly undermine soil erosion control. Weak enforcement of regulations and fragmented land management policies hinder effective action. Despite the Ethiopian Soil Conservation and Reforestation Program, weak enforcement has led to issues such as illegal logging and land encroachment. In 2022, deforestation in the Amhara region due to poor oversight increased erosion rates by 30% (Kassaye, 2024). The lack of a unified land-use approach further complicates conservation efforts, as seen in the SNNPR, where erosion rates increased by 40% in areas without integrated conservation measures (Ersedo, 2021). Funding gaps, such as those seen in Oromia in 2023, further reduce the effectiveness of conservation programs (Yadeta, 2023). In general weak enforcement of environmental regulations and fragmented land management policies are the main obstacles to effective soil erosion control. This section highlights the need for stronger regulatory enforcement, cohesive land management, and strategic investment in conservation. Policy reforms that encourage multi-stakeholder collaboration and provide funding for soil conservation projects are essential to tackling erosion effectively. This understanding lays the groundwork for the next section, examine the wide-ranging impacts of soil erosion, highlighting the urgency of implementing effective mitigation measures.

The review explores the multifaceted drivers of soil erosion in the Ethiopian Highlands, emphasizing climate variability, deforestation, unsustainable land use, population pressure, and infrastructural expansion. The reviewed literature underscores the role of intense rainfall, exceeding 200 mm per hour, as a primary catalyst, exacerbated by deforestation rates that triple erosion in exposed areas. Most of the literature indicates that steep slopes and fragile volcanic soils, particularly Andosols and Nitisols, show heightened erosion vulnerability, with erosion rates reaching up to 50 tonnes per hectare annually. Comparatively, deforestation emerges as a major contributing factor due to its direct exposure of soil to runoff, aligning with studies that report a 45-tonne per hectare erosion rate in deforested regions. The review also reveals that poor agricultural practices, such as deep tillage and overgrazing, significantly intensify erosion, especially on marginal lands. These findings call for comprehensive policy reforms integrating reforestation, terracing, and sustainable land-use practices to mitigate erosion and enhance agricultural resilience in the Ethiopian Highlands.

3.4 Significant environmental and socio-economic impacts of soil erosion in the ethiopian highlands

3.4.1 Land degradation and loss of arable land

Soil erosion in Ethiopia is not just an environmental concern; it is an economic and social crisis that threatens agricultural productivity and local economies on an alarming scale. The Ethiopian highlands face a staggering reduction in agricultural productivity of approximately 20% due to soil erosion, translating to an annual economic loss of nearly $1.2 billion in agricultural output alone (Wassie, 2020). Cumulative direct costs, including the depletion of topsoil nutrients and lowered livestock capacity, have reached $7 billion in a single decade (2000–2010), with indirect costs from reduced water quality and infrastructure damage compounding this burden (Reda and Hailu, 2017). In addition to the economic losses, the environmental costs are also staggering, undermining natural resource sustainability and development. The consequences of erosion extend far beyond agriculture. Sedimentation in reservoirs, for instance, has reduced storage capacity by up to 30%, undermining Ethiopia's water management infrastructure and hindering development (Kidane and Alemu, 2015). Socio-economically, erosion-driven land degradation has forced the abandonment of over 1.5 million hectares of arable land from 1982 to 2006, driving poverty up by 15% in highly impacted rural areas (Borrelli et al., 2017). In the Tigray region alone, communities report a 40% decrease in crop yields and a 25% increase in land abandonment over 2 decades, causing average *per capita* income to plummet by $50 annually in affected zones (Tsegaye, 2019).

Yet interventions demonstrate real potential. Evidence from successful soil conservation programs, such as those in the Debre Birhan area, shows that proactive soil management can yield tangible results. Soil conservation measures, such as terracing and reforestation, have led to a 30% improvement in soil stability and a 15% boost in crop productivity (Rawat and Tekleyohannes, 2021). These interventions highlight the possibility of reversing land degradation and stabilizing food production when large-scale efforts are implemented. To curb these critical losses, Ethiopia urgently needs coordinated, region-specific soil conservation strategies to restore soil health, stabilize food production, and bolster economic resilience across the highlands. The severity of soil erosion in Ethiopia's highlands is not just an environmental issue; it is a threat to agricultural sustainability, economic stability, and community livelihoods. Given the significant economic losses and socio-economic impacts, proactive and large-scale soil conservation strategies are necessary to restore arable land, enhance agricultural productivity, and protect the livelihoods of affected communities. The findings underscore the importance of both government and community-driven actions in addressing this crisis.

3.4.2 Loss of soil fertility

Soil erosion in the Ethiopian highlands is an escalating crisis with devastating impacts on agricultural productivity, economic stability, and food security. Each year, nutrient-rich topsoil is lost, severely undermining crop yields. In the Blue Nile basin alone, 14 kg/ha of nitrogen and 6.8 kg/ha of phosphorus are eroded annually, directly reducing agricultural output (Getnet and Mulu, 2021). The Ruba Gered watershed suffers similar losses, with rill erosion stripping 41.4 kg/ha of organic matter and 2.4 kg/ha of nitrogen, intensifying fertility challenges and increasing reliance on external aid (Gebreselassie et al., 2016). This soil degradation costs Ethiopia 10%–11% of its agricultural GDP annually, equating to $106 million in losses (Conijn et al., 2019). Soil erosion also inflates water management costs, as sedimentation reduces reservoir capacities, necessitating costly dredging (Giorgis et al., 2018), with Tigray dams experiencing a 20%–30% decrease in lifespan due to silting (Gebremeskel et al., 2018). Social impacts are severe: annual soil loss drives a 2.2% land productivity decline, reducing agricultural GDP by 2%–3% and the national GDP by 1% (Tsegaye, 2019). In Tigray, farmers experience up to a 50% yield drop, leading to a 15% poverty spike among smallholders (Zenebe et al., 2023), while pastoralists face a 25% herd reduction, which undermines household incomes and worsens malnutrition (Tilahun, 2021). In Gule Sub-Watershed, annual soil loss of 90.6 kg/ha has resulted in a 20% maize yield decline, forcing farmers into urban migration for survival (Nyssen et al., 2015).

Yet, there is hope. Integrated soil conservation efforts in Debre Birhan have significantly improved soil stability by 30% and increased productivity by 15% (Rawat and Tekleyohannes, 2021). These outcomes demonstrate the efficacy of evidence-based interventions that not only restore soil fertility but also revive agricultural productivity, enhance food security, and improve rural livelihoods. These measures emphasize the importance of scaling up soil conservation strategies to address the broader challenges of soil fertility degradation in Ethiopia. The ongoing erosion of soil fertility in Ethiopia has severe economic, agricultural, and social implications. Losses in soil nutrients and fertility, coupled with significant economic costs, highlight the urgent need for targeted soil conservation measures. The evidence from Debre Birhan provides a strong case for scaling up such efforts across the Ethiopian highlands to mitigate the impact of soil erosion and foster long-term agricultural productivity and food security.

3.4.3 Reduced agricultural productivity

Ethiopia's escalating soil erosion crisis poses a critical threat to agricultural stability, food security, and the national economy. Soil erosion leads to a staggering loss of one billion tonnes of fertile soil annually, with subsequent productivity drops of 2.2% per year, resulting in 2%–3% reductions in agricultural GDP and a 1% decline in national GDP (Haregeweyn et al., 2015; Gomiero, 2016). The erosion not only depletes crop yields but also pushes farmers deeper into poverty and food insecurity, exemplified by 33% wheat yield drops due to climate-induced shifts in precipitation and temperature patterns (Bezu, 2020). The crisis is further compounded by Ethiopia's dependence on rain-fed, smallholder farming, which is increasingly vulnerable to climate impacts. This sector is crucial, supplying 73% of raw materials for domestic industries and generating 85% of export revenue (Goba et al., 2022). In addition, livestock production declines, which directly affects pastoral communities and exacerbates malnutrition. Population pressures, land fragmentation, and climate change accelerate soil erosion, amplifying this already severe situation. If not addressed, this situation could have devastating long-term consequences on the livelihoods and economic stability of millions.

The reduction in agricultural productivity due to soil erosion is not just an environmental issue; it is an urgent socio-economic crisis that demands immediate, large-scale interventions. Specific soil management practices and adaptation strategies are essential to mitigate this crisis. These include the establishment of contour plowing and terracing to slow water runoff and reduce erosion on steep slopes, which have been effective in many parts of Ethiopia (Teku et al., 2024a). Agroforestry, integrating trees with crops, not only prevents soil erosion but also improves soil fertility and water retention, supporting both agricultural productivity and biodiversity (Walden et al., 2024). Check dams can capture water and sediment, reducing runoff and enhancing water availability for irrigation (Haregeweyn et al., 2015). Cover crops and vegetative buffers have also shown significant promise in reducing soil erosion, particularly on highly degraded lands (Beyene et al., 2019). Additionally, rainwater harvesting systems can improve water availability during dry periods, supporting the resilience of smallholder farming to erratic weather patterns (Goba et al., 2022). These strategies, when integrated into a comprehensive soil management framework, can help stabilize soil, enhance food security, and reduce the economic costs of soil erosion, ensuring a sustainable agricultural future for Ethiopia.

3.4.3.1 Impact on biodiversity

Soil erosion in Ethiopia's highlands has contributed significantly to the degradation of biodiversity, leading to the loss of vital habitats and a decline in species populations. The removal of nutrient-rich topsoil diminishes plant diversity and disrupts ecosystems that sustain a wide range of wildlife. Endemic species, such as *Erica arborea* and *Hypericum revolutum*, have faced population declines due to habitat loss driven by soil erosion (Kidane, 2022). Additionally, erosion has fragmented habitats, isolating species like the Ethiopian wolf (*Canis simensis*) and Gelada baboon (*Theropithecus gelada*), making it harder for them to find food and breeding grounds. This isolation has led to a reduced genetic diversity and increased vulnerability to extinction (Gidey, 2019). The loss of biodiversity has also diminished essential ecosystem services, including water filtration, nutrient cycling, and carbon sequestration. In particular, the destruction of forests has decreased the capacity of ecosystems to regulate water flow, heightening the risks of flooding and reducing water availability during dry periods (Yaynemsa, 2023). These impacts not only undermine ecological resilience but also jeopardize the livelihoods of communities who depend on these ecosystems for agriculture, grazing, and other resources.

The loss of biodiversity due to soil erosion exacerbates the vulnerability of Ethiopia's ecosystems. The degradation of habitats and loss of species threaten both ecological stability and the livelihoods of local communities. Immediate conservation measures are essential to mitigate these impacts. Specific measures include the restoration of degraded ecosystems through reforestation and afforestation programs, focusing on native species that help stabilize soil and restore biodiversity (Gidey, 2019). The implementation of buffer zones around critical habitats can reduce soil erosion and protect vulnerable species by providing safe corridors for wildlife movement. Invasive species control is another necessary measure to reduce competition with native species and facilitate ecosystem recovery (Kidane, 2022). Furthermore, sustainable land management practices, such as agroforestry and contour farming, can reduce soil erosion and improve habitat quality for wildlife. These practices, when combined with community-based conservation efforts and ecosystem restoration projects, can help rehabilitate habitats and improve biodiversity resilience in the Ethiopian highlands. These actions are critical not only for ecological stability but also for the livelihoods of local communities dependent on these ecosystems.

3.4.3.2 Increasing vulnerability to climate change

Soil erosion significantly heightens the Ethiopian highlands' vulnerability to climate change, creating a feedback loop that worsens both soil degradation and climate impacts (Teku and Eshetu, 2024). As erosion removes topsoil and vegetation cover, the land's ability to retain moisture and regulate local temperatures is severely compromised, reducing resilience to both droughts and heavy rainfall (Tullu and Habtegebriel, 2023). This degradation leads to diminished infiltration rates, which results in increased runoff during storms and a heightened risk of floods (Molla et al., 2019). During droughts, the reduced soil moisture capacity exacerbates the impacts of dry spells, further stressing crops and ecosystems (Teku et al., 2024b). Additionally, climate change accelerates erosion processes by intensifying rainstorms and prolonged dry spells, which in turn exposes the land to further degradation (Tullu and Habtegebriel, 2023). This vicious cycle weakens the natural adaptive capacity of both the environment and local communities, making it more difficult to cope with climate variability and hinder efforts for effective climate adaptation (Bezu, 2020). The interaction between soil erosion and climate change presents a formidable challenge, amplifying the impacts of both. The compounded effects on agricultural productivity, water resources, and biodiversity underline the need for integrated land management and climate adaptation strategies.

3.4.4 Risk of landsliding and flooding

The Ethiopian highlands are increasingly susceptible to landslides and flooding due to soil erosion. The removal of vegetation and destabilization of soil result in increased surface runoff, which contributes to landslides and exacerbates flooding (Assefa, 2018). Steep terrain combined with eroded soils reduces the land's ability to absorb rainfall, leading to higher volumes of water runoff that overwhelm river systems and lead to destructive floods. Studies have shown a correlation between soil erosion and an increase in both landslide occurrences and flood events, which have detrimental impacts on infrastructure, agriculture, and community safety (Mewa and Mengistu, 2022; Tsegaye, 2019). In general the growing risk of landslides and flooding due to soil erosion presents significant threats to infrastructure, agricultural productivity, and human safety. Urgent action is needed to implement soil conservation strategies to reduce these risks and protect vulnerable communities.

3.4.5 Water resource degradation

Soil erosion in the Ethiopian highlands is critically undermining key water bodies, which has far-reaching economic and

environmental consequences across various regions. For instance, Lake Tana, Ethiopia's largest lake, now faces severe sedimentation, which has reduced its water storage capacity by approximately 15%, diminishing water quality and clarity (Wassie, 2020). The sedimentation disrupts local fisheries, reduces water quality, and limits the lake's utility for both irrigation and hydroelectric power production (Kidane and Alemu, 2015). Similar degradation has been observed in the Awash River Basin, where erosion has led to a 30%–40% reduction in the Koka Dam's storage capacity. This loss has escalated maintenance costs and limited water availability for irrigation in the Oromia, Amhara, and Afar regions (Tsegaye, 2019).

In Oromia's Lake Ziway, sediment-induced eutrophication leads to algal blooms that reduce oxygen levels, threatening aquatic ecosystems and impacting the livelihoods of fish-dependent communities. Additionally, erosion in the Upper Blue Nile Basin has caused sediment deposits that now threaten to diminish the natural appeal of the Tis Issat Waterfall and pose a silting risk to the Grand Ethiopian Renaissance Dam (GERD) (Kidane and Alemu, 2015). Likewise, in the Gibe River Basin of SNNPR, sedimentation has reduced the efficiency of the Gibe III Dam, necessitating expensive dredging operations. Downstream, these sediments also jeopardize the ecosystem of Lake Turkana, impairing fish breeding habitats and the livelihoods of local communities (Gurmu, 2022), emphasizes the need for comprehensive watershed management strategies that include soil erosion control as a key component. Water management policies must integrate soil conservation efforts to protect the functionality of critical water bodies, thus ensuring long-term water security, sustainable agricultural practices, and the preservation of local economies. Investments in erosion control measures, such as afforestation, terracing, and sustainable farming techniques, can be critical in mitigating these water resource challenges. This understanding lays the bases for the next section, discuss on solutions that directly address these impacts, focusing on strategies that are both preventative and restorative, ensuring that our efforts to combat soil erosion are comprehensive and sustainable.

The review draws on extensive literature to reveal that soil erosion in the Ethiopian highlands severely impacts agricultural productivity, economic stability, biodiversity, and water resources, with land degradation and reduced arable land emerging as the most profound drivers of socio-economic vulnerability. Most of the literature indicates that erosion-driven land degradation has resulted in a 20% drop in agricultural productivity, contributing to $1.2 billion in annual economic losses and the abandonment of 1.5 million hectares of farmland. The reviewed literature underscores the erosion of nutrient-rich topsoil, with nitrogen and phosphorus depletion significantly reducing crop yields and livestock capacity. Comparatively, the review highlights that soil erosion-induced sedimentation reduces reservoir storage by up to 30%, threatening Ethiopia's water infrastructure and accelerating biodiversity loss. This review also reveals that biodiversity loss, driven by habitat degradation, exacerbates ecological instability and threatens endemic species. These findings show that coordinated, large-scale soil conservation strategies such as terracing, reforestation, and sustainable land management are crucial for reversing land degradation, restoring soil fertility, and mitigating erosion's cascading socio-economic impacts.

3.5 Sustainable solutions for mitigating soil erosion in the Ethiopian Highlands

3.5.1 Soil and water conservation structures

3.5.1.1 Terracing

Terracing has proven highly effective in conserving soil in Ethiopia's highlands, reducing erosion by over 50% in targeted areas and boosting soil moisture and crop yields, as shown in studies by Debie et al. (2018). By decreasing slope gradients and runoff, terracing supports sustainable agriculture, though its success varies by region specific factors like topography and rainfall. Integrating terracing with practices like contour plowing and agroforestry enhances soil stability, biodiversity, and farmer income. Adaptations, such as stone bunds and Fanya juu terraces, have shown particular promise on steep slopes with high rainfall (Debie et al., 2018). Despite high initial costs, terracing offers strong long-term returns through increased productivity and potential carbon credits. Addressing economic and technical barriers *via* incentives and community support can ensure terracing's broad, effective adoption across Ethiopia's highlands.

3.5.1.2 Stone bunds

Stone bunds are a critical and highly effective soil conservation method in the Ethiopian highlands, dramatically reducing soil erosion, enhancing soil fertility, and retaining moisture. Quantitative findings show that stone bunds implemented in highland areas decreased soil erosion by over 40%, significantly boosting agricultural yields and reducing land degradation (Taye et al., 2018). A Study by Teressa, 2017, further validate their impact, highlighting a notable increase in soil moisture retention. When integrated with other conservation practices, such as In review vegetative strips and contour plowing, stone bunds' efficacy in controlling erosion and retaining soil is amplified. Yet, challenges like high construction costs, limited local knowledge, and infrastructural gaps impede widespread adoption (Alemayehu et al., 2020). A recent cost-benefit analysis demonstrates, however, that the long-term gains such as increased crop productivity and income opportunities from carbon credits more than justify the initial investment (Taye et al., 2018). Overcoming barriers through community training, financial incentives, and infrastructural support is essential for scaling up stone bunds across Ethiopia's diverse highland regions, ensuring long-term resilience against soil erosion.

3.5.1.3 Check dams

Check dams are an essential, cost-effective soil conservation solution in Ethiopia's highlands, significantly reducing soil erosion and improving agricultural productivity by slowing water flow, trapping sediment, and stabilizing gullies. In the Debre Mawi watershed, check dams reduced sediment transport and increased soil moisture, substantially improving crop yields and rehabilitating degraded lands (Guyassa et al., 2017). Research across the highlands reveals that check dams, when integrated with other practices like terracing and vegetative measures, can multiply their impact slowing runoff, enhancing water infiltration, and reducing flood risks downstream (Lucas-Borja et al., 2021). For example, adding vegetative measures around check dams further stabilizes the soil

and fosters biodiversity, enhancing both ecological and economic benefits. Yet, adoption is hindered by economic and infrastructural constraints, such as construction costs and limited technical expertise, especially among smallholder farmers. Cost-benefit analyses indicate that, despite initial costs, the long-term gains in productivity and potential income from ecosystem services justify the investment (Guyassa et al., 2017). Overcoming these challenges through community engagement, capacity building, and government support is essential to harnessing the full potential of check dams as a sustainable soil management tool across Ethiopia's highlands.

3.5.2 Vegetative measures

3.5.2.1 Agroforestry

Integrating trees and shrubs into farmlands emerges as an essential strategy to combat soil erosion in Ethiopia's Highlands, where the deep roots of selected vegetation stabilize soil, boost fertility, and retain moisture, ultimately enhancing productivity. Studies show agroforestry can reduce erosion rates by up to 30% while also increasing yields and supporting biodiversity (Amare et al., 2019; Hussein, 2024). Indigenous species like Faidherbia albida and Cordia africana not only curb erosion but provide vital resources like fodder and fuelwood, which strengthen local economies (Getachew and Mulatu, 2024). Combined with techniques like terracing and grass strips, agroforestry maximizes soil retention, boosts water infiltration, and supports sustainable agriculture (Waldén et al., 2024; Beyene et al., 2019). Tailoring agroforestry to specific soil types and rainfall patterns in the region is essential for success. Yet, adoption is hindered by high upfront costs, delayed returns, and limited access to quality seedlings and technical support. Cost-benefit analyses highlight that the long-term gains in crop yield, soil health, and potential carbon credits far outweigh initial expenses (Nigussie et al., 2019). Enhanced extension services, financial incentives, and market access for agroforestry products are crucial steps to promote wider adoption, positioning agroforestry as a sustainable solution to the critical challenge of soil erosion in Ethiopia's highlands.

3.5.2.2 Afforestation and reforestation

Afforestation and reforestation are not only beneficial but essential strategies in the Ethiopian Highlands to counter severe soil erosion that endangers agricultural sustainability and ecological resilience. These practices reestablishing forests and planting trees play a crucial role in stabilizing soil and reducing surface runoff, a critical factor in a region already grappling with intense degradation. For instance, the Humbo Assisted Natural Regeneration Project demonstrated a 30% reduction in soil erosion, significantly improving soil structure, moisture retention, and fertility (Eshete et al., 2023). Besides strengthening biodiversity and supporting carbon sequestration, these initiatives can provide economic benefits through carbon credit sales. Integrating tree planting with soil conservation methods like contour plowing and terracing further maximizes erosion control and agricultural productivity, as integrated strategies often outperform isolated efforts (Haregeweyn et al., 2015). Tailoring these approaches to local conditions such as selecting native tree species and adapting techniques to the region's topography enhances both ecological stability and economic gains. Yet, barriers remain; high initial costs for seedlings and maintenance discourage smallholder farmers (Hurni et al., 2016). However, a comprehensive analysis shows that the long-term benefits, including higher crop yields and carbon credit revenue, outweigh the upfront investments. Addressing financial and infrastructural constraints through strengthened extension services, financial incentives, and community-based initiatives is vital for sustainable implementation. By scaling up these In review efforts, Ethiopia can address the urgent challenge of soil erosion, paving the way for a more sustainable and resilient future.

3.5.2.3 Cover crops

In the Ethiopian Highlands, cover crops have emerged as a crucial solution to counter the escalating problem of soil erosion, where steep slopes and intense rainfall contribute to rapid soil degradation. Unlike crops grown for harvest, cover crops provide essential ground cover, dramatically reducing runoff, enhancing soil structure, and boosting fertility an indispensable support for both soil health and agricultural productivity. Recent studies reveal impressive results: research by Molla and Desta (2022) in the Central Rift Valley shows that using legumes as cover crops can reduce soil erosion by up to 45%, while simultaneously enhancing soil fertility and water retention. Similarly, in the Southern Highlands, cover crops have contributed to a 30% increase in crop yields, fostering resilience in farming systems (Desta et al., 2021). Integrating cover crops with practices like contour plowing and terracing amplifies these benefits, creating a powerful strategy for erosion control and productivity (Adimassu et al., 2017). However, realizing the full potential of cover crops requires tailoring crop choices to the local topography and climate, such as selecting drought-resistant legumes and deep-rooted grasses suited to specific regions (Haregeweyn et al., 2015). While cover crops offer transformative benefits, adoption faces obstacles. High upfront costs for seeds and maintenance can deter smallholder farmers, and limited access to quality seeds and technical know-how further hinder effective use (Molla and Desta, 2022). Yet, cost-benefit analyses indicate that long-term gains, including healthier soil, improved yields, and reduced dependency on chemical fertilizers, outweigh initial investments. Additionally, cover crops contribute to carbon sequestration, providing economic incentives through potential carbon credits. Programs by the Ethiopian Agricultural Transformation Agency are now working to address these barriers through financial support, training, and community initiatives. For the Ethiopian Highlands, where soil erosion poses an existential threat, cover crops are more than an agricultural technique they are an essential strategy for protecting both agricultural productivity and environmental health. Immediate, coordinated action is needed to harness their proven benefits and secure a sustainable future for these fragile landscapes.

3.5.2.4 Grass strips

Grass strips, also known as vegetative buffer strips, offer an essential yet underutilized solution to the severe soil erosion plaguing the Ethiopian Highlands. In this erosion-prone landscape, marked by steep slopes and heavy rainfall, soil degradation threatens both agricultural productivity and food security. Recent studies reveal the remarkable impact of grass strips: in the Anjeni watershed, their implementation led to a

30% reduction in soil erosion by trapping sediment and slowing runoff (Umer et al., 2019). Grass strips also improve soil moisture retention and crop productivity, thereby boosting soil fertility and reducing gully formation (Bekele et al., 2023). For optimal results, these strips should be combined with contour plowing and terracing. Contour plowing decelerates water flow, and terracing minimizes slope gradients, while grass strips stabilize soil and enhance moisture retention, together increasing productivity by up to 25% (Tsegaye and Bharti, 2023). Success depends on adapting these practices to local conditions, with careful grass species selection based on soil type, climate, and erosion challenges. Research suggests that targeted grass species choices significantly boost erosion control, especially under heavy rainfall (Negasa, 2022). Although initial costs for seeds and maintenance pose economic challenges, long-term benefits like improved soil health and crop yields justify the investment, with potential returns exceeding costs by 150% (Bekele et al., 2023; Negasa, 2022). Yet, adoption is hindered by economic constraints and a lack of technical knowledge among farmers. Addressing these barriers, the Ethiopian Agricultural Transformation Agency provides subsidies, training, and technical assistance, fostering the spread of grass strips as a vital conservation strategy. The urgency to address soil erosion in the Ethiopian Highlands cannot be overstated; the widespread adoption of grass strips is essential to preserve agricultural productivity and ensure environmental sustainability for millions in this vulnerable region.

3.5.3 Improved agricultural practices

3.5.3.1 Contour plowing

Contour plowing, which involves plowing along natural contour lines, emerges as a crucial strategy to combat soil erosion in Ethiopia's erosion-prone Highlands. This method creates natural barriers that reduce runoff, enhance water infiltration, and prevent sediment loss. In the Anjeni watershed, contour plowing has reduced soil erosion by 40%, also improving soil moisture and crop yields (Kebede et al., 2023). When combined with cover crops, this technique significantly boosts soil structure and fertility, resulting in a 50% rise in soil fertility a compelling case for its broader adoption (Molla and Sisheber, 2017; Tilahun, 2021). Integrated with terracing and vegetative strips, contour plowing further curtails soil erosion and promotes productivity, providing a sustainable In review solution for the highlands' unique challenges (Molla and Sisheber, 2017). Tailoring contour plowing to local topography and soil types enhances its effectiveness, especially in steep areas where additional measures like check dams may be needed (Kebede et al., 2023). While initial costs can be high, long-term gains from reduced erosion and increased yields can exceed investments by up to 150% (Tilahun, 2021). However, economic barriers, limited equipment, and a lack of technical knowledge hinder adoption (Akale et al., 2017). To address these challenges, the Ethiopian Agricultural Transformation Agency provides essential support, including subsidies, training, and equipment access, to empower farmers in adopting contour plowing as a cornerstone of sustainable agriculture (Molla and Sisheber, 2017). Immediate action on soil conservation through contour plowing is essential to safeguard the region's agriculture, food security, and environmental sustainability for millions.

3.5.3.2 Conservation tillage

Conservation tillage is an urgent and essential agricultural practice for combating soil erosion in the erosion-prone Ethiopian Highlands. This method minimizes soil disturbance, enhancing water infiltration and drastically reducing surface runoff a critical necessity given the region's steep slopes and heavy rainfall. Recent studies reveal its dramaticindicates that conservation tillage reduces soil loss by over 40% compared to conventional methods (Haregeweyn et al., 2015). This significant reduction is due to improved soil structure and organic matter preservation, which facilitate water absorption and mitigate the impact of heavy rainfall. Moreover, the practice of leaving crop residues on the soil surface offers vital protective cover, further diminishing erosion risk. The increased organic matter not only enhances soil structure and microbial activity but also boosts fertility, making the soil more resilient to erosion (Mihretie et al., 2022). To maximize its effectiveness, conservation tillage should be integrated with other practices like contour plowing and terracing. This combination creates a synergistic effect, significantly improving soil conservation outcomes. Additionally, incorporating vegetative measures such as cover crops can further bolster soil health and reduce erosion.

However, effective implementation requires tailoring conservation tillage to local environmental conditions, such as topography and soil type. For example, in areas with steep slopes or heavy rainfall, additional measures like check dams may be necessary (Adimassu et al., 2017). A cost-benefit analysis highlights the economic viability of conservation tillage, where initial investments in equipment and inputs are often outweighed by long-term benefits, including increased crop yields and reduced soil rehabilitation costs. Studies suggest that the economic returns justify these investments, making it a financially sound choice for farmers (Mihretie et al., 2022). Despite its benefits, adoption faces challenges, including economic constraints and a lack of local expertise. Overcoming these barriers necessitates financial support, such as subsidies, alongside training programs to enhance farmers' skills. Organizations like the Ethiopian Agricultural Transformation Agency are pivotal in addressing these challenges, promoting the widespread adoption of conservation tillage as a critical solution for soil erosion in the Ethiopian Highlands. The urgency to adopt conservation tillage cannot be overstated; it represents a crucial step in safeguarding the agricultural productivity and environmental sustainability of the Ethiopian Highlands. Figure 4 below illustrates different types of soil erosion mitigation in the Ethiopian highlands.

3.6 Policy and practice implications of soil erosion in the Ethiopian Highlands

Soil erosion in the Ethiopian Highlands poses significant threats to agricultural productivity, environmental sustainability, and local livelihoods, necessitating a multifaceted policy and practice response. Addressing this issue requires the development of comprehensive frameworks that integrate policy strengthening, incentivized sustainable practices, and community-driven solutions. As summarized in Table 1, successful soil conservation relies on enhancing legal structures, fostering collaboration among stakeholders, and embedding educational programs that empower local communities. These initiatives, grounded in research and

TABLE 1 Analyzed summary of policy and practice implications of soil erosion in the Ethiopian Highlands.

Policy/Practice implications	Description
Strengthening Policy Frameworks	Develop comprehensive soil and water conservation policies with clear regulations, incentives, and legal frameworks. Address barriers to implementation and set quantifiable goals to enhance agricultural productivity and environmental stewardship. Include long-term sustainability strategies and robust M&E mechanisms (Nigussie et al., 2019)
Incentivizing Sustainable Practices	Encourage sustainable practices through financial incentives (subsidies, grants) to alleviate barriers for farmers. Develop flexible microfinance options and sustainable funding sources to ensure longevity, complemented by targeted technical support for effective soil management (Adimassu et al., 2017)
Enhancing Community Involvement and Capacity Building	Empower communities through Community-Based Natural Resource Management (CBNRM) that integrates traditional and modern practices. Involve community members in planning and monitoring to ensure culturally aligned and sustainable initiatives, leveraging local knowledge for effective soil conservation (Gebremeskel et al., 2018)
Education and Awareness Programs	Implement educational programs integrated into national curricula and public campaigns to provide farmers with essential knowledge for soil conservation. Tailor strategies to local contexts and promote community engagement to ensure long-term success and improved agricultural productivity (Goba et al., 2022)
Research and Development (R&D)	Support R&D initiatives to foster innovation in soil conservation practices. Identify and test new technologies tailored to local conditions, ensuring evidence-based strategies that enhance agricultural productivity and address environmental challenges. Collaborate among stakeholders to overcome funding barriers (Erkossa et al., 2022)
Integrating Governmental and Non-Governmental Efforts	Facilitate multi-stakeholder collaboration to enhance effectiveness in addressing soil erosion. Engage various actors (government, communities, NGOs) to share knowledge and resources, ensuring initiatives align with local needs and promote shared responsibility in conservation efforts (Zenebe et al., 2023)
Monitoring and Evaluation (M&E)	Establish comprehensive M&E frameworks focusing on specific indicators to assess and improve soil conservation strategies. Incorporate local knowledge and technological tools for data collection and stakeholder engagement to ensure interventions remain effective and adaptable over time (Wolancho, 2015)
Legal and Regulatory Frameworks	Develop robust legal reforms to enforce soil conservation practices and regulations. Integrate traditional land tenure systems with modern laws and provide economic incentives to encourage sustainable land management. Strengthen oversight and accountability for conservation practices through regular inspections (Haregeweyn et al., 2015)
Long-Term Sustainability	Focus on adaptive management to ensure long-term sustainability of soil conservation efforts. Prioritize practices that address immediate challenges while building resilience against future threats. Establish dedicated funding mechanisms to support ongoing initiatives and ensure community engagement in conservation practices (Debie et al., 2024)

development, highlight the importance of adaptive management and robust monitoring and evaluation mechanisms to ensure long-term effectiveness (Adimassu et al., 2017; Gebremeskel et al., 2018). By bridging gaps between governmental and non-governmental efforts, Ethiopia can mitigate soil erosion's detrimental impacts, fostering resilient landscapes and sustainable agricultural growth.

3.7 Case studies and examples

The Ethiopian Highlands are characterized by diverse landscapes and agricultural practices, making them particularly vulnerable to soil erosion. Over the years, various soil conservation policies and practices have been implemented across different regions to combat this issue. These initiatives range from integrated watershed management to community-based approaches and agroforestry, each tailored to address the specific environmental and socio-economic conditions of the region. The following Table 2 presents a summary of key case studies and examples from different parts of the Ethiopian Highlands, highlighting the soil conservation practices adopted, the successes achieved, and the challenges encountered in each region. These case studies provide valuable insights into the effectiveness of soil conservation efforts and underscore the importance of continued innovation and community involvement in sustainable land management.

4 Conclusion and recommendations

4.1 Conclusion

In the Ethiopian Highlands, soil erosion manifests through water, wind, and gravitational processes, resulting in sheet, rill, and gully erosion. The prevalence of these erosive processes is

TABLE 2 A summary of soil conservation practices adopted, the successes achieved, and the challenges encountered in the Ethiopian Highlands.

Region	Soil conservation policies and practices	Challenges and successes
Tigray Region	Integrated Watershed Management: Practices like terracing, stone bunds, and reforestation have improved soil and water conservation	Successful in reducing soil erosion and enhancing productivity; however, scaling up remains a challenge due to limited resources and need for sustained community engagement
Amhara Region	Soil Conservation and Sustainable Land Management: Implementation of soil bunds, area closures, and agroforestry	Increased vegetation cover and reduced degradation; challenges include long-term maintenance and need for continuous technical support
Southern Nations, Nationalities, and Peoples' Region (SNNPR)	Community-Based Soil Conservation: Participatory approaches involving local farmers in conservation measures like check dams	Significant reductions in soil loss and improved yields; challenges include ensuring equitable participation and benefits among community members
Oromia Region	Agroforestry as a Soil Conservation Strategy: Integrating trees into agricultural landscapes to reduce erosion	Improved soil fertility and household incomes; however, land tenure insecurity limits farmers' investment in long-term practices
Eastern Highlands	Fanya Juu Terracing and Soil Fertility Management: Digging trenches and building embankments to control runoff	Effective in reducing erosion and enhancing soil fertility; however, labor intensity and maintenance needs pose challenges for smallholder farmers

driven by a combination of environmental and anthropogenic factors, including deforestation, overgrazing, poor agricultural practices, slope and topography, rainfall variability, soil degradation, inadequate soil conservation measures, and population pressure. The impacts of soil erosion are profound, affecting the region's agriculture and fragile ecosystem. These include the loss of arable land, decreased crop yields, water resource degradation, biodiversity decline, increased climate vulnerability, heightened risk of landslides and flooding, loss of cultural heritage, social displacement, migration, and economic costs related to remediation efforts. To mitigate soil erosion effectively, an integrated approach is essential. This approach should combine structural, vegetative, and improved agricultural practices, such as terracing, stone bunds, check dams, agroforestry, cover crops, grass strips, contour plowing, and conservation tillage. These measures not only control soil erosion but also enhance soil fertility, improve water management, and contribute to sustainable agricultural productivity. Addressing the challenges of soil erosion requires a cohesive strategy that integrates robust policy frameworks, active community involvement, and coordinated efforts between governmental and non-governmental organizations. Developing detailed policies, incentivizing sustainable practices, enhancing community capacity, fostering multi-stakeholder collaboration, and implementing comprehensive monitoring systems are critical to reducing soil erosion and promoting sustainable land management. Ensuring the region's long-term sustainability involves implementing effective land management practices, promoting agroforestry, restoring degraded ecosystems, and building community resilience.

4.2 Recommendations

4.2.1 National and regional policies

Policymakers must implement specific, measurable soil conservation policies. For example, the Ethiopian Soil Conservation and Reforestation Program should be expanded to include mandatory land-use zoning that restricts farming on steep slopes and encourages the use of sustainable agricultural practices. A targeted subsidy program could provide incentives for adopting conservation practices like terracing, agroforestry, and cover cropping. The Drought Resilience and Sustainable Livelihoods Program in the Ethiopian highlands has demonstrated success in providing subsidies for conservation, and similar programs should be scaled up (Admassie and Abebaw, 2021). Setting quantifiable goals, such as reducing soil erosion by 20% over 5 years, will make these programs more effective.

4.2.2 Empowering community-based organizations (CBOs)

CBOs play a crucial role in local soil and water conservation. Successful models from the Gamo Highlands show that communities have been able to design and implement conservation practices tailored to their specific needs (Roka, 2020). Providing financial and technical support to CBOs, along with capacity-building programs that focus on both traditional and modern conservation methods, will ensure long-term sustainability. The success of community-managed forests in the Bale Mountains offers a compelling example of local ownership leading to effective conservation outcomes (Yadeta, 2023).

4.2.3 Educational programs and workshops

Developing context-specific training programs is essential for the widespread adoption of soil conservation techniques. For instance, the World Agroforestry Centre (ICRAF) has successfully worked with Ethiopian farmers in areas like Sheka Zone to teach agroforestry techniques that enhance soil fertility and reduce erosion (Ababa, 2015). Such programs should be extended to rural schools and local farmers through interactive workshops and field demonstrations, focusing on methods proven to work in Ethiopian landscapes. Additionally, incorporating soil conservation into national curricula for agricultural and environmental studies will prepare future generations to continue the conservation efforts.

4.2.4 Multi-stakeholder platforms

Building collaborative platforms will amplify the efforts of policymakers, local communities, NGOs, and the private sector. A good example is the Ethiopian Forest Action Program, where partnerships between government, NGOs, and the private sector

have led to successful large-scale tree planting efforts (Mayengo et al., 2024). Regular consultations and joint planning sessions between these groups will foster alignment and ensure that the diverse resources and expertise available are effectively used.

4.2.5 Monitoring and evaluation (M&E)

Establishing robust M&E frameworks is critical to measure the effectiveness of soil conservation efforts. The Ethiopian Agricultural Transformation Agency (ATA) has developed an M&E system that tracks progress on agricultural development projects, including soil conservation (Naidoo and Kodjo, 2023). By integrating specific metrics, such as the number of hectares treated with soil conservation techniques and improvements in soil quality, Ethiopia can better monitor the impact of conservation initiatives. Regular evaluations should ensure that conservation measures are effective and can be adjusted when necessary.

4.2.6 Community-driven initiatives

The involvement of local communities in conservation projects is paramount. Successful interventions, such as the land rehabilitation projects in the Gedeo Highlands, where local communities used traditional methods of water management combined with modern practices, show the importance of community-driven planning processes (Tadesse, 2023). Empowering local groups with technical assistance from NGOs can further ensure that conservation measures are tailored to the specific needs of the communities, improving the likelihood of successful implementation.

4.2.7 Role of the private sector

The private sector has a pivotal role to play in promoting sustainable soil conservation practices. Agribusinesses and corporations should invest in innovative solutions, such as drone technology for monitoring soil health and remote sensing for early detection of erosion hotspots. Companies like Ethio Telecom have shown how private-sector engagement can support large-scale initiatives. Partnerships between the private sector, NGOs, and government should focus on scaling up soil conservation practices and integrating them into corporate social responsibility (CSR) programs.

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