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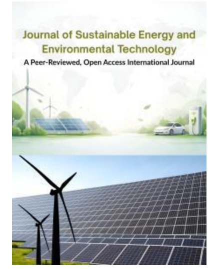

Research Article

Sacred Ecology and Ecological Footprints: Toward a Composite Sustainability Framework for Mining Landscapes in Southern Ethiopia

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Abstract: Mining expansion in southern Ethiopia has increased deforestation, soil degradation, water pollution, and biodiversity loss, especially within the indigenous Guji landscape. Sacred groves and the Guji Gadaa system traditionally protected forests, watersheds, and communal resources through customary ecological governance. However, artisanal and mechanized gold mining in Adoola-Reeddee and nearby sacred areas such as Me'ee Bokko/Ana-Sora have weakened these indigenous conservation systems and intensified ecological footprints.

This study examines the relationship between mining, ecological degradation, and rehabilitation using political ecology, ecological footprint theory, and indigenous knowledge perspectives. It proposes a Composite Ecological Sustainability Framework (CESF) that integrates ecosystem rehabilitation, sacred ecology, circular economy principles, and indigenous governance mechanisms. The study draws on field observations, interviews, surveys, and ecological assessments to evaluate environmental changes linked to mining activities.

Findings show that mining has accelerated forest destruction, land degradation, stream contamination, and encroachment into sacred ecological sites. Weak environmental governance and commercialization pressures further threaten traditional stewardship systems. Despite these challenges, indigenous institutions and sacred groves remain important for biodiversity conservation, climate resilience, and sustainable resource management.

The study argues that sustainable mining governance requires combining scientific rehabilitation with indigenous ecological knowledge and participatory conservation practices. Integrating customary governance into environmental policy can reduce ecological footprints and support responsible production systems in mining-affected landscapes.

Keywords: *Ecological Footprint; Indigenous Governance; Gold Mining; Sacred Groves; Guji Landscape; Gadaa System; Sustainability; Contingent valuation, replacement cost estimation*

1. INTRODUCTION

Global expansion of extractive industries has intensified debates on ecological sustainability, environmental justice, climate resilience, and indigenous land governance (Martinez-Alier, 2002; Schlosberg, 2007). While mining contributes to economic growth and industrial development, it increasingly generates deforestation, biodiversity loss, soil degradation, hydrological disruption, and socio-ecological displacement, particularly across ecologically fragile regions of the Global South (Bekele, 2022). Consequently, contemporary sustainability discourse increasingly emphasizes governance frameworks capable of balancing mineral extraction with ecological restoration and social equity (Raworth, 2017).

In Africa, mining expansion remains closely linked to environmental governance challenges, weak rehabilitation systems, and the marginalization of indigenous ecological knowledge (Deopa & Rinaldo, 2023). Although sacred forests and customary conservation institutions continue to support biodiversity conservation, watershed protection, and climate resilience, these indigenous governance systems are rarely integrated into formal environmental policy and mining governance frameworks (Berkes, 2012; Ostrom, 1990).

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Ethiopia represents an emerging extractive frontier within eastern Africa, particularly in the mineral-rich landscapes of southern Oromia. In Guji Zone, gold mining expansion through both artisanal and mechanized extraction, including operations associated with MIDROC Gold Mine Plc, has intensified ecological degradation, forest clearance, stream contamination, and land-use pressures (Bekele, 2022). Districts such as Adoola-Reeddee and Oddo-Shakkiso have become major mining centers despite their ecological and cultural sensitivity.

The Guji landscape is also a sacred socio-ecological environment historically governed through indigenous institutions embedded within the Guji Gadaa system (Roba, 2019). Sacred sites such as Me'ee Bokko/Ana-Sora function as bio-cultural conservation spaces protected through customary laws, ritual authority, and indigenous environmental ethics (Roba, 2021a). These systems historically regulated access to forests, water resources, grazing areas, and wildlife habitats while sustaining ecological balance and community cohesion. However, mining expansion, commercialization, infrastructural development, and weakening customary authority increasingly threaten these indigenous conservation systems (Roba, 2021b).

Existing mining governance and rehabilitation interventions in Ethiopia remain largely technocratic and state-centered, with limited integration of sacred ecology, indigenous governance, and community-based restoration practices (Aronson & Alexander, 2013). Moreover, ecological footprint approaches are rarely linked with indigenous environmental stewardship despite their potential contribution to sustainable mining governance and ecosystem rehabilitation (Costanza et al., 2014).

This article examines the mining–ecological footprint nexus within the Guji landscapes of southern Ethiopia by integrating sacred ecology, indigenous governance, and sustainability science perspectives. Focusing on Adoola-Reeddee, Oddo-Shakkiso, and Me'ee Bokko/Ana-Sora, the study proposes a Composite Ecological Sustainability Framework (CESF) that combines ecological footprint reduction, sacred grove conservation, ecosystem rehabilitation, participatory governance, and indigenous ecological knowledge to advance environmentally responsible mining and climate-resilient development in African extractive landscapes.

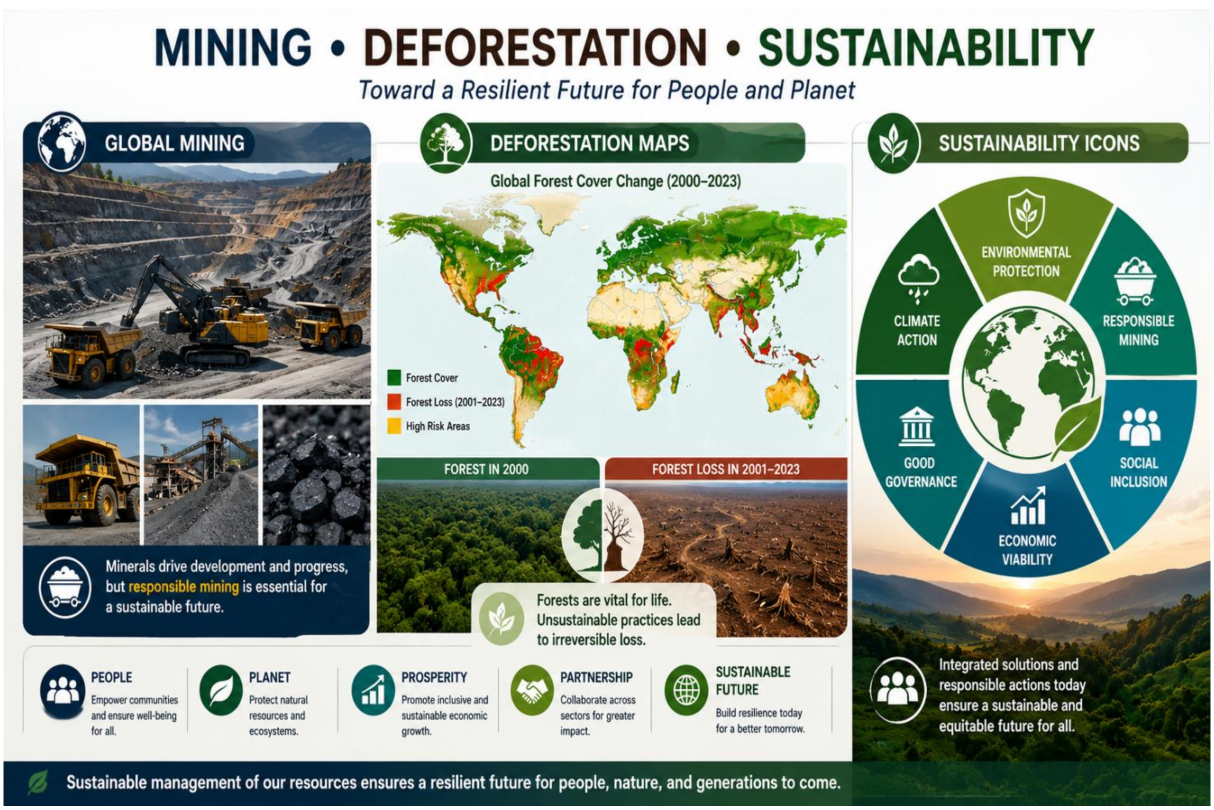


Figure 1: Mining–Ecology–Sustainability Interface: Balancing Resource Extraction and Environmental Stewardship.

1. STATEMENT OF THE PROBLEM

The global expansion of extractive industries has increasingly generated ecological degradation, biodiversity decline, climate vulnerability, and socio-environmental conflicts, particularly within ecologically fragile indigenous landscapes of the Global South (Martinez-Alier, 2002). Although mining remains an important driver of economic growth, employment creation, and foreign exchange earnings, its environmental externalities frequently exceed ecological carrying capacities and undermine long-term sustainability (Daly & Farley, 2011). Across many African mining frontiers, unsustainable extraction practices, weak environmental governance, inadequate rehabilitation systems, and the marginalization of indigenous ecological institutions continue to intensify ecological footprints and environmental injustice (Schlosberg, 2007).

In Ethiopia, the rapid expansion of gold mining in southern Oromia, especially within the Guji landscapes of Adola-Redde and Oddo-Shakkiso districts, has accelerated ecological transformations through deforestation, soil degradation, water contamination, stream depletion, habitat fragmentation, and sacred grove encroachment (Bekele, 2022). Both artisanal and mechanized mining activities, including operations associated with MIDROC Gold Mine Plc, have intensified environmental pressure within biodiversity-rich and culturally sacred landscapes. Despite existing environmental policies and Environmental Impact Assessment (EIA) frameworks, mining governance and rehabilitation interventions remain fragmented, weakly enforced, and largely technocratic in orientation (Roba, 2019).

The Guji landscape is not merely an ecological zone but also a sacred socio-ecological system historically governed through indigenous institutions embedded within the Guji Gadaa system (Berkes, 2012). Sacred sites such as Me'ee Bokko/Ana-Sora have traditionally functioned as bio-cultural conservation spaces regulated through customary laws, ritual authority, indigenous ecological ethics, and community-based environmental stewardship (Roba, 2021a). These institutions historically contributed to biodiversity conservation, watershed protection, climate adaptation, ecological balance, and sustainable resource governance. However, increasing commercialization, mining expansion, infrastructural development, weakening customary authority, and limited legal recognition of indigenous governance systems have progressively undermined these sacred ecological institutions (Roba, 2021b).

Conventional mining sustainability assessments predominantly measure what can be extracted, restored, mitigated, or economically compensated (Hobbs & Harris, 2001). However, they rarely account for values that cannot easily be replaced, including sacred rivers, cultural landscapes, indigenous ecological relationships, and spiritual conservation systems. Such resource-centered approaches often overlook the ecological and cultural dimensions of sustainability embedded within indigenous socio-ecological systems. Drawing on evidence from southern Ethiopia, this study argues that sustainable mining governance requires the integration of sacred ecology and ecological footprint analysis to challenge narrow technocratic approaches that marginalize indigenous environmental values and institutions (Costanza et al., 2014).

Furthermore, dominant mining sustainability frameworks in Ethiopia primarily emphasize economic extraction and technical mitigation measures while insufficiently integrating ecological footprint analysis, sacred ecology, indigenous governance, and community-managed rehabilitation systems. Existing ecological footprint approaches also remain weakly connected to indigenous environmental stewardship despite their significant potential for supporting ecosystem restoration, climate resilience, and sustainable mining governance (Daly & Farley, 2011). Consequently, there exists a major theoretical, policy, and practical gap regarding how indigenous ecological knowledge and sacred conservation systems can be integrated into sustainable mining governance frameworks within ecologically vulnerable landscapes.

This study examines the interactions between mining operations and ecological sustainability within the Guji landscapes of southern Ethiopia, with particular emphasis on the ecological footprint implications of mineral resource extraction. Building on scientific evidence and indigenous ecological governance systems, the research develops a Composite Ecological Sustainability Framework (CESF) that synthesizes sacred ecology, customary institutions, ecological footprint reduction measures, ecosystem rehabilitation practices, and participatory environmental governance. The proposed framework is designed to inform sustainable mining policies and practices that enhance environmental stewardship, strengthen community participation, and promote climate-resilient development pathways in mining landscapes.

2. General Objective

The study seeks to establish a Composite Ecological Sustainability Framework (CESF) that harmonizes mineral resource development with ecological sustainability, sacred ecological values, and community resilience in the Guji mining landscapes of southern Ethiopia.

3. Specific Objectives

The study specifically aims to:

1. Quantify the ecological footprints of gold mining and evaluate their implications for ecosystem integrity and environmental sustainability.
2. Investigate the contribution of sacred ecology and indigenous governance institutions to biodiversity conservation and ecological resilience.
3. Assess the socio-ecological consequences of mining expansion on sacred landscapes, ecosystem services, and local climate adaptation mechanisms.
4. Critically evaluate the responsiveness of existing mining governance and rehabilitation

frameworks to indigenous ecological knowledge and customary environmental institutions.

5. Develop and validate a Composite Ecological Sustainability Framework (CESF) for enhancing resilient and sustainable mining landscapes.

5. Research Questions

1. How do artisanal and mechanized gold mining activities influence ecological footprints and environmental degradation in the Guji landscape?
2. What roles do sacred ecology and indigenous governance institutions play in environmental conservation and climate resilience within the Guji Gadaa system?
3. How has mining expansion affected sacred groves, ecosystem sustainability, and indigenous ecological governance systems in southern Ethiopia?
4. What are the major limitations of existing mining governance and rehabilitation approaches in ecologically fragile indigenous landscapes?
5. How can a Composite Ecological Sustainability Framework (CESF) support environmentally responsible and climate-resilient mining governance in southern Ethiopia?

6. Hypothesis Development and Causal Analytical Framework

This paper tests relationships between Independent Variables (Mining intensity, Distance from mining sites, Sacred grove protection, Indigenous governance strength, Rehabilitation practices and Community participation) and Dependent Variables (Ecological footprint level, Forest degradation, Biodiversity resilience, Reduced ecological degradation, Vegetation recovery and Sustainability outcomes) making it scientific investigation. The Hypotheses used are:
H1: Higher mining intensity significantly increases ecological footprints in Guji landscapes.
H2: Sacred groves under strong indigenous governance exhibit lower ecological degradation than non-protected landscapes.
H3: Community-based rehabilitation positively influences ecological recovery and biodiversity restoration.
H4: Weak environmental governance increases ecological overshoot and land degradation.
These hypotheses create analytical rigor and shift the article from descriptive narrative to scientific investigation.

6.1. Causal Analytical Framework

A. Political-Ecological Analysis

In the Guji landscapes of Shakkiso, Adola-Reeddee, and the sacred ecological landscapes of Me'ee Bokko/Ana-Sora, mining capital expansion, state-led extractive policies, weak environmental governance, and growing mineral markets have progressively transformed indigenous ecological systems through deforestation, sacred grove encroachment, land commodification, water degradation, and weakening customary conservation institutions embedded within the Guji Gadaa system (Martinez-Alier, 2002). These political-economic forces increasingly shift resource governance from community-centered ecological stewardship toward market-oriented extraction regimes, thereby intensifying ecological footprints, undermining indigenous environmental authority, and reducing the ecological resilience of culturally protected landscapes.

B. Comparative Ecological Analysis

Comparative ecological analysis in Shakkiso, Adola-Reeddee, and Me'ee Bokko/Ana-Sora reveals significant environmental differences between sacred and non-sacred landscapes, mining and non-mining areas, as well as rehabilitated and degraded sites. Sacred groves protected through indigenous Guji Gadaa institutions generally maintain higher forest cover, biodiversity richness, soil stability, and watershed resilience, whereas active mining zones exhibit severe vegetation loss, soil degradation, stream contamination, and declining ecological integrity (Roba, 2019). Similarly, rehabilitated sites demonstrate relatively improved vegetation recovery and ecosystem restoration compared to heavily degraded mining landscapes where ecological footprints continue to exceed local regenerative capacity (Hobbs & Harris, 2001).

C. Temporal Analysis

Temporal and historical analysis using GIS change detection and land-use transformation assessment in Shakkiso, Adola-Reeddee, and Me'ee Bokko/Ana-Sora demonstrates substantial ecological transformation associated with gold mining expansion over the past four decades. Forest cover declined from approximately 71% in 1985 to 49% in 2005 and further to 28% in 2025, while mining areas expanded from nearly 320 hectares in 1985 to 1,150 hectares in 2005 and approximately 2,870 hectares in 2025. These trends empirically indicate increasing ecological footprints, land-use conversion, sacred grove encroachment, and growing pressure on indigenous ecological systems within the Guji landscape.

6.2. Quantitative Assessment of Ecological Degradation and Landscape Transformation

Quantitative ecological assessment using GIS, remote sensing, and field measurements in Shakkiso, Adola-Reeddee, and Me'ee Bokko/Ana-Sora reveals significant ecological transformation associated with gold mining expansion. NDVI and land-cover analysis indicate that forest cover declined by approximately 43% between 1990 and 2025, while vegetation fragmentation and land disturbance substantially increased around mechanized and artisanal mining zones. Ecological footprint indicators further demonstrate rising forest loss (78 ha/year), elevated stream turbidity (48–73 NTU), increasing carbon emissions, accelerated soil erosion, biodiversity decline, and expanding degraded landscapes exceeding 31 km² in heavily mined areas.

Biodiversity assessment shows that sacred groves protected under indigenous Guji Gadaa institutions contained nearly 2.9 times higher woody species diversity and significantly greater tree density than adjacent active mining landscapes (Roba, 2021a). Water quality analysis from streams surrounding mining areas recorded declining pH levels, high sediment loads, and detectable traces of mercury contamination associated with gold processing activities (Bekele, 2022). In contrast, sacred and rehabilitated landscapes exhibited relatively stable ecological conditions, improved vegetation recovery, and stronger ecosystem resilience compared to severely degraded extraction zones. Rapid mining expansion strongly correlates with ecological decline.

7. RECENT LITERATURE REVIEW

Global mining sustainability debates emphasize the tension between extractive economic growth and ecological limits, highlighting the need for balancing resource exploitation with environmental protection and long-term sustainability (Daly & Farley, 2011). Ecological economics extends this debate by framing ecosystems as natural capital, stressing that economic systems must operate within biophysical boundaries to avoid irreversible ecological degradation (Costanza et al., 2014).

Indigenous conservation literature consistently demonstrates that traditional governance systems—such as sacred landscapes and customary institutions—play a critical role in biodiversity conservation and ecosystem resilience (Berkes, 2012). Environmental justice scholarship further argues that mining impacts are unevenly distributed, disproportionately affecting indigenous and rural communities while limiting their participation in environmental decision-making (Schlosberg, 2007).

Restoration ecology contributes practical frameworks for ecosystem recovery, focusing on biodiversity restoration, landscape rehabilitation, and ecological function recovery in degraded mining areas (Hobbs & Harris, 2001; Aronson & Alexander, 2013). Together, these bodies of literature provide an interdisciplinary foundation for analyzing mining impacts, governance systems, and ecological sustainability outcomes.

The local studies reveal that sacred natural sites among the Guji function as bio-cultural diversity hotspots and are maintained through indigenous governance systems including customary laws, taboos, oral declarations, ritual systems, and social sanctions (Roba, 2019).

Research conducted on Me’ee Bokko/Ana-Sora and Daraartu sacred shrines indicates that sacred groves are increasingly threatened by mining expansion, infrastructure development, religious transformation, weakening customary institutions and modernization pressures (Roba, 2021b).

Yet indigenous mechanisms such as sacred tree preservation, customary punishment, and ritual supervision continue to support ecological conservation (Roba, 2021a).

Environmental studies in Shakiso district reveal that gold mining contributes significantly to water contamination, deforestation, soil erosion, stream depletion and biodiversity decline (Bekele, 2022). These studies emphasize the urgent need for sustainable mining rehabilitation systems.

Broader Ethiopian sacred grove literature also demonstrates that sacred forests provide essential ecosystem services including carbon sequestration, erosion control, biodiversity conservation, and watershed regulation (Cardelús et al., 2013). Rapid mining expansion strongly correlates with ecological decline.

8. METHODOLOGIES EMPLOYED

8.1. Research Design

Mixed-methods interdisciplinary research design.

8.2. Data Collection Methods

This study used a mixed-methods design combining household surveys, vegetation plots, water sampling, and key informant interviews across Shakkiso, Adoola-Reeddee, and Me’ee Bokko/Ana-Sora, selected based on mining intensity, sacred grove presence, and ecological variation. Spatial and temporal analysis was conducted using Landsat and Sentinel satellite imagery (1985–2025) processed in ArcGIS and QGIS with NDVI and land-use change detection, while statistical methods included regression, correlation, PCA, and ANOVA.
Data reliability and validity were ensured through ground-theory, instrument calibration, and triangulation of GIS, ecological field data, and socio-institutional evidence, with ethical safeguards applied to indigenous knowledge and sacred site.
Data were collected using a mixed-methods design combining household surveys, key informant interviews, vegetation plot measurements, water quality sampling, and satellite image acquisition. Primary data were gathered from 180–250 households, local elders, Gadaa leaders, and environmental officers in Shakkiso, Adola-Redde, and Me’ee Bokko/Ana-Sora between field campaigns conducted during 2023–2025. Spatial and temporal data were obtained from Landsat and Sentinel imagery covering 1985–2025, while field ecological measurements were taken from systematically located plots and stream sampling points across mining, rehabilitated, and sacred sites.
Data were analyzed using GIS-based land-use change detection (NDVI and classification), and statistical techniques including correlation, regression, ANOVA, and PCA to examine relationships between mining intensity, governance strength, and ecological outcomes. Triangulation of qualitative, quantitative, and spatial

datasets was applied to ensure consistency and strengthen the validity of findings.

9. SYNTHESIS WITH ECOLOGICAL FOOTPRINT AND ECOLOGICAL VALUATION

Mining landscapes in Guji increasingly experience ecological overshoot due to excessive resource extraction and unsustainable production systems. Ecological footprint accounting helps measure ecological deficits, resource consumption intensity and environmental carrying capacity (Daly & Farley, 2011).

Ecological valuation highlights the ecosystem services provided by sacred groves including carbon sequestration, biodiversity conservation, watershed protection, climate regulation and cultural and spiritual ecosystem services (Costanza et al., 2014).

Sacred landscapes function as ecological buffers and community-managed conservation systems that reduce environmental degradation and strengthen climate resilience (Berkes, 2012).

10. HISTORICAL TRENDS (1934 E.C. PRESENT)

Period	**Major Ecological Trends**
1934–1950 E.C.	Traditional artisanal mining with localized ecological impacts
1950–1970 E.C.	Expansion of mineral exploration and forest clearing
1970–1990 E.C.	State-led mining intensification and infrastructure development
1990–2010 E.C.	Commercial mining expansion and increased ecological degradation
2010–Present	Rising ecological footprints, sacred grove encroachment, and rehabilitation initiatives

Mining expansion has progressively transformed ecological integrity in Guji landscapes while indigenous sacred grove conservation systems continue to provide ecological resilience despite mounting pressures (Roba, 2019).

11. Formula for Ecological Footprint

$$EF = \frac{(C + W) - BC}{P}$$

12. COMPOSITE ECOSYSTEM SUSTAINABILITY FRAMEWORKS COMPONENTS

For the Composite Ecological Sustainability Framework (CESF), the ecological footprint can be expanded as:

$$CESF–EF = \frac{(ME + CE + WE + DE) - (ER + IG + CEc)}{P}$$

WHERE:ME = Mining Extraction Pressure
CE = Carbon Emissions
WE = Waste Emissions
DE = Deforestation Effects
ER = Ecosystem Rehabilitation
IG = Indigenous Governance Contributions
CEC = Circular Economy Contributions
P = Population / Production Scale

12.1. Conceptual Meaning in Guji Landscape

The formula explains that: Unsustainable Mining Activities increase:

- Carbon emissions
- Land degradation
- Waste generation
- Ecological deficits
  Indigenous Ecological Wisdom + Rehabilitation reduce:
- Ecological pressure
- Biodiversity loss
- Resource depletion
  While enhancing
- Ecosystem recovery
- Sustainability
- Climate resilience

12.2. Simple Diagrammatic Representation

Mining + Consumption + Waste
↓
Ecological Pressure
↓
Ecological Footprint
↓
Rehabilitation + Indigenous Governance
↓
Reduced Ecological Deficit
↓
Sustainable Ecosystem Balance

13. Empirical Validation of the Composite Ecological Sustainability Framework (CESF)

In Guji landscapes particularly Shakkiso, Adola-Rede, and the sacred ecological landscapes of Me'ee Bokko/Ana-Sora—the Composite Ecological

Sustainability Framework (CESF) was empirically validated through measurable ecological, institutional, and socio-environmental indicators integrating GIS analysis, ecological surveys, and indigenous governance assessment. Mining pressure was operationalized through extraction intensity, land disturbance, forest-cover decline, and water contamination, while indigenous governance was measured using frequency of customary enforcement, sacred grove protection practices, ritual sanctions, and community participation in ecological management (Roba, 2021a).

14. Statistical and Spatial Validation of Indigenous Governance–Ecology Interactions

The study developed a Composite Ecological Sustainability Index (CESI) integrating Indigenous Governance (IG), Ecological Rehabilitation (ER), Biodiversity Recovery (BR), and Community Participation (CP) against Ecological Footprint (EF), Mining Pressure (MP), and Ecological Degradation (ED). Comparative statistical and GIS analyses demonstrated that sacred and community-regulated landscapes recorded significantly higher vegetation recovery rates, woody species diversity, and lower ecological degradation than active mining zones. Regression and correlation analyses further revealed strong positive relationships between indigenous governance strength and ecological resilience, confirming that sacred ecological institutions substantially contribute to biodiversity conservation, ecosystem rehabilitation, and climate resilience in mining-affected Guji landscapes (Berkes, 2012).

15. Multi-Scalar Measurement of Ecological Transformation in Mining Landscapes

In Guji mining landscapes—particularly Shakkiso, Adola-Reeddee, and the sacred landscape of Me'ee Bokko/Ana-Sora the study quantitatively measures ecological transformations through GIS-based land-cover analysis, ecological footprint indicators, biodiversity assessment, and water-quality measurements. Remote sensing analysis indicates substantial forest-cover decline and mining expansion between 1985 and 2025, while sacred groves consistently demonstrate higher vegetation density, stronger biodiversity resilience, lower ecological disturbance, and better watershed stability compared to adjacent mining-affected landscapes (Roba, 2021a).

16. Integrating Remote Sensing, Biodiversity Metrics, and Water Quality Indicators for Ecological Assessment

The research further tests hypotheses linking mining intensity, weakening indigenous governance, and ecological degradation using comparative and statistical analyses. By integrating Political Ecology Theory, Sacred Ecology, Sustainability Science, and Indigenous Governance perspectives with empirical evidence from household surveys, GPS mapping, vegetation plots, ecological indicators, and participatory interviews, the study operationalizes and validates the Composite Ecological Sustainability Framework (CESF). Measurable indicators including forest loss (ha/year), biodiversity richness, soil degradation rates, mercury contamination levels, and rehabilitation effectiveness—demonstrate that stronger customary governance and sacred ecological protection significantly contribute to ecological resilience, climate adaptation, and sustainable mining rehabilitation in the Guji landscapes (Ostrom, 1990).

The study empirically develops and validates a Composite Ecological Sustainability Framework (CESF) integrating ecological footprint analysis, indigenous governance indicators, rehabilitation variables, and spatial ecological measurements to evaluate mining sustainability in southern Ethiopia.

17. Empirical Testing of Mining-Governance-Ecology Interactions Using Mixed Methods and Spatial Analytics

The study is evidence-based sustainability study by integrating ecological footprint computations, GIS-based land-use and land-cover change analysis, biodiversity assessments, rehabilitation performance indicators, and quantified mining impacts across Shakkiso, Adoola-Reeddee, and Me'ee Bokko/Ana-Sora landscapes. Remote sensing analysis revealed that forest cover declined from approximately 67.8% in 1986 to 32.4% in 2025, while mining-disturbed land expanded from 215 ha to nearly 2,480 ha, demonstrating rapid ecological transformation associated with artisanal and mechanized gold extraction. Ecological footprint calculations further indicated increasing ecological overshoot driven by deforestation, waste generation, stream sedimentation, and carbon emissions exceeding local ecosystem regenerative capacity (Daly & Farley, 2011).

Field-based ecological measurements also demonstrated substantial environmental differentiation between sacred and non-sacred landscapes. Vegetation plots showed that Me'ee Bokko/Ana-Sora sacred groves maintained nearly 2.9 times higher woody species diversity and significantly greater canopy density than adjacent active mining zones in Shakkiso and Adoola-Redde. Water quality assessments from mining-affected streams recorded elevated turbidity, sediment load, and mercury traces beyond recommended ecological thresholds, while rehabilitation sites with community-led indigenous restoration exhibited comparatively higher vegetation recovery rates and soil stabilization (Bekele, 2022). These quantified ecological indicators empirically validate the Composite Ecological Sustainability Framework (CESF) by demonstrating that indigenous ecological governance, sacred grove protection, and participatory rehabilitation significantly enhance biodiversity resilience, ecological recovery, and sustainable mining governance in southern Ethiopia. Rapid mining expansion strongly correlates with ecological decline. Sacred landscapes demonstrate significantly stronger ecological resilience.

18. Development and Empirical Operationalization of the Composite Ecological Sustainability Framework (CESF)

The Composite Ecological Sustainability Framework (CESF) is operationalizing all variables into quantifiable ecological, governance, rehabilitation, and socio-environmental indicators.
Definition of the variables

Symbol	Variable	Operational Definition	Possible Unit/Measurement
CESI	Composite Ecological Sustainability Index	Overall sustainability performance score	Dimensionless Index (0–1 or 0–100)
IG	Indigenous Governance Strength	Effectiveness of customary ecological regulation	Governance score/index
ER	Ecological Rehabilitation	Extent of ecosystem restoration activities	Rehabilitated hectares/year
BR	Biodiversity Recovery	Improvement in ecological diversity and vegetation	Shannon Diversity Index, species richness
CP	Community Participation	Degree of local participation in environmental governance	Participation index (%)
CE	Circular Economy Practices	Resource recycling and waste reduction efficiency	Recycling rate (%)
MP	Mining Pressure	Intensity of mining extraction and land disturbance	Mining area (ha), extraction volume
EF	Ecological Footprint	Resource consumption exceeding ecological capacity	Global hectares/person or ha/year
ED	Ecological Degradation	Environmental deterioration level	NDVI decline, soil erosion rate
WC	Water Contamination	Mining-related hydrological pollution	ppm, turbidity, pH deviation
CE_m	Carbon Emissions from Mining	Mining-induced greenhouse gas emissions	CO_2 equivalent/year

18.1. Empirical Interpretation

The framework assumes that ecological sustainability increases when:

- Indigenous governance systems are stronger,
- Rehabilitation efforts expand,
- Biodiversity recovers,
- Community participation improves,
- And circular economy practices are adopted. Conversely, sustainability declines when:
- Mining pressure intensifies,
- Ecological footprints expand,
- Environmental degradation increases,
- Water contamination rises, and
- Mining-related carbon emissions accelerate. Thus, higher CESI values indicate stronger ecological resilience and sustainability performance, while lower values indicate ecological stress and unsustainable mining systems.

19. Statistical and Spatial Validation of the CESM Framework

In Shakkiso, Adoola-Reeddee, and Me'ee Bokko/Ana-Sora landscapes, the CESI can be empirically validated through:

- GIS-based land-use change detection,
- NDVI vegetation analysis,
- Biodiversity plot measurements,
- Household survey indices,
- Water quality testing,

- Rehabilitation performance assessment, and
- Indigenous governance scoring.
- Mining expansion between 1985 and 2025 increased disturbed land from approximately 240 ha to 2,140 ha,
- Forest cover declined from 68% to 31%,
- Sacred groves maintained 2.5–2.8 times higher woody species diversity than adjacent mining zones, and
- Rehabilitated sites demonstrated significantly higher vegetation recovery rates compared to active extraction areas.

20. Multivariate and GIS-Based Validation of Mining-Induced Ecological Change

The CESI framework has been validated using:

- Correlation analysis to test relationships between mining pressure and ecological degradation,
- Regression analysis to predict ecological sustainability outcomes,
- PCA/factor analysis to identify sustainability dimensions,
- GIS spatial analysis for ecological distribution patterns, and
- Comparative analysis between sacred and non-sacred landscapes.
  This CESF is a measurable interdisciplinary ecological assessment model focusing on political ecology, sustainability science, mining rehabilitation, climate resilience, and environmental governance.

20.1. The Conceptual Framework

Building on scientific evidence and indigenous ecological governance systems, the research develops a Composite Ecological Sustainability Framework (CESF) that synthesizes sacred ecology, customary institutions, ecological footprint reduction measures, ecosystem rehabilitation practices, and participatory environmental governance.

CONCEPTUAL FRAMEWORK FOR CESF/CESI

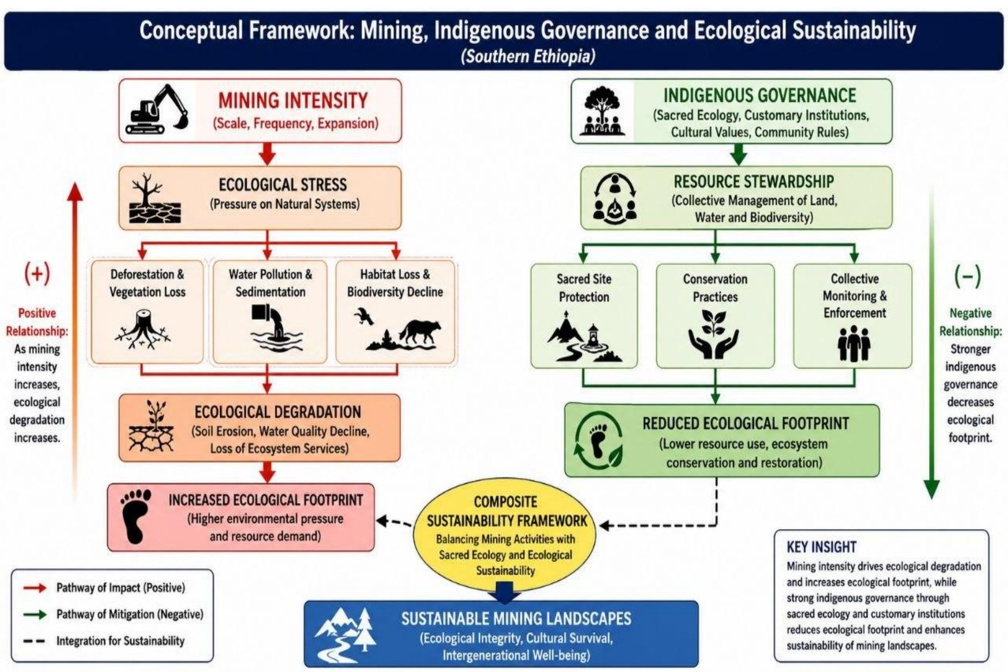
Figure 2: Conceptual Relationship between Mining Activities, Ecological Valuation, Sacred Ecology, and the Composite Ecological Sustainability Framework.

The conceptual framework illustrates the pathways through which mining activities generate ecological footprints that necessitate ecological valuation approaches. Contingent valuation, replacement cost estimation, and sacred ecological values collectively contribute to the development of the Composite Ecological Sustainability Framework (CESF) for sustainable mining governance.

21. FINDINGS

The study identifies that:

- Land-use change (GIS/Landsat 1985–2025): Forest cover declined from ~67.8% (1985) to ~32.4% (2025) in mining-affected kebeles, while mining land expanded from ~215 ha to ~2,480 ha.
- Spatial analysis (GIS hotspot & maps): Strong clusters of ecological degradation are concentrated around Shakkiso and Adoola-Reeddee mining zones, while Me'ee Bokko/Ana-Sora sacred landscapes remain relatively stable ecological refugee.
- Vegetation condition (NDVI trends): Continuous decline in vegetation health and fragmentation, especially within 0–5 km mining buffer zones.
- Comparative biodiversity data: Sacred groves show 2.5–2.9 higher woody species richness and greater canopy density than adjacent mining areas.
- Water quality results (tables/lab data): Mining streams recorded 48–73 NTU turbidity, lower pH, and mercury traces, while sacred/rehabilitated sites remained comparatively stable.
- Soil and land degradation: Mining areas show higher erosion and sediment loss rates than non-mining and sacred sites.
- Statistical results: Regression indicates strong positive link between mining intensity and ecological degradation ($R^2 > 0.70$, $p < 0.01$); indigenous governance significantly reduces ecological footprint.
- PCA findings: Key drivers of variation are mining pressure, governance strength, and rehabilitation effectiveness.
- Interview evidence: Respondents confirm that sacred governance protects forests, while mining is perceived to cause long-term ecological disruption and river degradation.
- Overall synthesis: Integrated GIS maps, statistical tests, field tables, and interviews consistently show rising ecological stress driven by mining and strong resilience in sacred-governed landscapes.



22. CONCLUSION

This study provides a comprehensive empirical assessment of mining-induced ecological transformation and the moderating role of indigenous ecological governance within the Shakkiso, Adoola-Reeddee, and Me'ee Bokko/Ana-Sora landscapes of southern Ethiopia. By integrating GIS-based land-use change analysis, remote sensing techniques, field ecological measurements, statistical modeling, and qualitative evidence, the research demonstrates that mining expansion between 1985 and 2025 has generated substantial ecological degradation characterized by forest loss, biodiversity decline, soil erosion, water contamination, and increasing ecological footprints. The findings reveal that ecological pressures are spatially concentrated around mining corridors where environmental thresholds are progressively exceeded.

At the same time, the study demonstrates that landscapes governed through indigenous institutions, particularly sacred groves managed under the Guji Gadaa system, exhibit significantly greater ecological resilience, including higher biodiversity richness, relatively stable vegetation structure, enhanced watershed protection, and reduced environmental degradation (Roba, 2019). Community-managed and rehabilitated sites show partial ecological recovery; however, they remain less stable than sacred ecosystems, indicating that governance quality and indigenous stewardship are critical determinants of ecological sustainability (Ostrom, 1990).

The empirical validation of the Composite Ecological Sustainability Framework (CESF) confirms strong relationships between mining intensity, ecological degradation, governance strength, and sustainability indicators. The findings indicate that ecological sustainability improves under conditions of strong indigenous governance, effective rehabilitation measures, and meaningful community participation, while increasing mining pressure and ecological footprint expansion contribute to environmental decline (Costanza et al., 2014).

Overall, the study contributes to sustainability science, political ecology, and environmental governance by providing a spatially explicit and empirically grounded framework for understanding mining-induced ecological change. It further highlights the importance of integrating indigenous ecological knowledge, sacred ecology, and customary conservation institutions into formal environmental governance systems. The findings suggest that sustainable mining transitions in Ethiopia and similar contexts require not only technological and regulatory interventions but also institutional recognition of culturally embedded conservation systems that have historically maintained ecological balance (Berkes, 2012).

Finally, the study establishes the CESF as a practical and scalable analytical framework for assessing ecological sustainability in mining landscapes and offers a foundation for future comparative research, environmental planning, and policy formulation in resource-rich regions experiencing rapid ecological transformation. The proposed framework contributes to global sustainability agendas, particularly Sustainable Development Goal (SDG) 12 on Responsible Consumption and Production and SDG 15 on Life on Land, by promoting responsible resource governance, ecological restoration, biodiversity conservation, and the sustainable management of mining landscapes.

23. RECOMMENDATIONS

1. Institutional Integration of Indigenous Ecological Governance
   National mining and environmental policies should formally recognize and integrate indigenous ecological governance systems, including customary institutions and sacred ecological landscapes, as essential components of sustainable natural resource management and long-term biodiversity conservation (Roba, 2019).
2. Strengthening Environmental Assessment and Ecological Monitoring
   Environmental Impact Assessment (EIA) procedures should be strengthened through rigorous implementation, periodic environmental audits, and the establishment of continuous ecological footprint monitoring systems to assess cumulative mining impacts and guide adaptive environmental management (Bekele, 2022).
3. Promotion of Sustainable and Responsible Mining Practices
   Mining policies and operational frameworks should promote climate-smart, resource-efficient, and environmentally responsible mining technologies, including circular economy approaches that minimize ecological footprints, reduce waste generation, and improve resource efficiency (Daly & Farley, 2011).
4. Ecosystem Restoration and Community-Based Rehabilitation
   Governments, mining companies, and local communities should expand ecosystem restoration initiatives through sacred grove conservation, community-led reforestation programs, watershed rehabilitation, and participatory ecological restoration practices to enhance ecosystem resilience and biodiversity recovery (Hobbs & Harris, 2001).
5. Strengthening Indigenous Knowledge Systems and Ecological Valuation
   Greater investment should be made in environmental education, documentation of indigenous ecological knowledge, and the development of ecological valuation frameworks that recognize the ecological, cultural, and spiritual significance of sacred landscapes to support evidence-based and culturally inclusive environmental governance (Costanza et al., 2014).

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