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Assessing the Effects of Quarry Mining on Environmental Quality in Kalengwa Ward of Mufumbwe District

[1] Liberty Chilonga, [2] Silombe Mwenya
[1, 2] Department of Agriculture and Environmental Science, Information and Communications University (ICU), Zambia Research and Development Centre, Lusaka, Zambia

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Corresponding Author: **Liberty Chilonga**

Abstract
This study assessed the environmental effects of quarry mining in Kalengwa Ward, Mufumbwe District. Using a mixed-methods approach, the research combined quantitative environmental measurements, air quality, water quality, and noise levels, with socio-economic surveys and interviews. A sample of 100 respondents was drawn from a target population of 500 using Yamane's formula. Findings revealed severe environmental degradation, including elevated dust concentrations (PM10 and PM2.5 far exceeding WHO and ZEMA limits), excessive noise levels (up to 92 dB), and localized water quality anomalies such as high magnesium and selenium concentrations and petroleum hydrocarbon contamination in one borehole. Land degradation and biodiversity loss were evident around quarry sites. Weak enforcement of environmental regulations exacerbated negative effects. The study concludes that quarry mining in Kalengwa offers short-term economic gains but poses significant risks to sustainable development. Recommendations include stricter policy enforcement, dust and noise control measures, water protection strategies, community-based restoration programs, and adoption of sustainable quarrying practices to balance development with environmental and social well-being.

Keywords: Quarry Mining, Environmental Quality, Air Pollution, Water Contamination, Noise Pollution, Biodiversity Loss, Sustainable Development

1. Introduction

1.1 Background of Study

Quarry mining is among the most widespread extractive activities globally, playing a critical role in infrastructure development and economic growth. It involves the extraction of stones, gravel, sand, and aggregates for construction and industrial purposes. However, this activity often generates significant environmental and socio-economic challenges that require systematic assessment. Recent studies emphasize that while quarrying provides essential raw materials, its ecological footprint is substantial due to direct landscape alteration and ecosystem disruption (Kafu-Quvane & Mlaba, 2024; Taiwo & Ogunbode, 2024) [25, 52]. This research focuses on Kalengwa in Zambia, a region experiencing increased quarry mining, to examine both its benefits and associated risks. Globally, quarrying has expanded in response to rising demand for aggregates driven by urbanization, road construction, and housing projects (Ngilay & Flores, 2024; Bonful, *et al*., 2024 [5]). In Africa, including Zambia, quarry mining contributes to employment and local revenue generation but often lacks adequate environmental safeguards (Ogba-Amaugo, *et al*., 2020) [42]. Despite these economic benefits, poorly regulated quarrying has been linked to severe environmental degradation and social challenges, making it a subject of urgent scientific inquiry. From an environmental perspective, quarry operations disturb soil structure, accelerate erosion, and reduce vegetation cover (Taiwo & Ogunbode, 2024) [52]. Dust emissions from blasting and crushing elevate particulate matter (PM10 and PM2.5) beyond WHO thresholds, increasing respiratory health risks for nearby communities (Taiwo & Ogunbode, 2024) [52]. Water resources are similarly affected through sedimentation and chemical contamination, threatening aquatic ecosystems and household water security (Bonful, *et al*., 2024) [5] (Kafu-Quvane & Mlaba, 2024) [25]. These findings underscore the need for integrated environmental assessments to safeguard ecosystem integrity and long-term sustainability. Socio-economically, quarry mining presents a dual reality. On one hand, it creates employment and stimulates small-scale businesses such as transport and food vending (Ogba-Amaugo, *et al*., 2020) [42]. On the other hand, it displaces agricultural land, disrupts livelihoods, and exacerbates social inequalities, particularly in rural communities that dependent on subsistence farming (Shackleton, *et al*., 2019) [50]. Gender disparities also emerge, as quarry employment is often male-dominated, marginalizing women who rely on farming for income (Ogba-Amaugo, *et al*., 2020) [42].

In Zambia, quarrying has historically supported construction and infrastructure development, but enforcement of environmental regulations remains weak, especially in rural areas (Phiri & Tembo, 2020) [46]. Consequently, communities frequently bear the brunt of environmental and health impacts without commensurate socio-economic benefits. Kalengwa, located in Northwestern Province, exemplifies this tension: while quarrying offers economic opportunities, residents report growing concerns about dust pollution, water contamination, and loss of farmland (Taiwo & Ogunbode, 2024; Shackleton, *et al*., 2019) [52, 50].

This study therefore seeks to assess the dual effects of quarry mining in Kalengwa, environmental and socio-economic, using scientific methods to evaluate air and water quality, land degradation, biodiversity loss, and health indicators, alongside socio-economic outcomes such as income, employment, and community perceptions. By integrating these dimensions, the research aims to provide evidence-based recommendations for sustainable quarrying practices that balance development needs with environmental protection and community well-being. Understanding these interactions is essential for promoting responsible resource management and informing policy interventions in Zambia and similar contexts across sub-Saharan Africa.

1.2 Problem Statement

Quarry mining has become an important economic activity in developing regions such as Kalengwa in Zambia, providing essential aggregates for infrastructure development, including roads, housing, and industrial projects. However, existing evidence suggests that quarry operations often lead to land degradation, deforestation, dust emissions, water contamination, and noise pollution, all of which compromise ecosystem integrity and public health. Over the past decade, Kalengwa has experienced rapid expansion of quarrying activities driven by infrastructure projects in Northwestern Province. Community reports highlight issues such as loss of arable land, damage to roads from heavy trucks, and increased respiratory complications among residents. While the Zambia Environmental Management Agency (ZEMA) provides regulatory oversight, enforcement at the local level remains weak, allowing quarrying to proceed with minimal environmental safeguards. This regulatory gap has made it difficult to determine whether the socio-economic benefits of quarry mining outweigh its environmental and health costs. The absence of comprehensive, scientific assessments of these impacts limits the ability of policymakers and stakeholders to design effective interventions. Therefore, a systematic evaluation of environmental effects of quarry mining in Kalengwa is urgently needed to inform sustainable development strategies and regulatory frameworks.

1.3 Research Objectives

1.3.1 General Objective

The main objective of this study was to assess the effects of quarry mining on the environment in Kalengwa. The research adopted a primarily scientific approach by integrating environmental effect testing and assessment methodologies coupled with socio-economic surveys to generate reliable and objective findings.

1.3.2 Specific Objectives

1. To examine the environmental effects of quarry mining in Kalengwa, focusing on soil quality, vegetation cover, water resources, and air quality.
2. To assess the challenges associated with quarry mining, including employment, income levels, health, and social well-being of local residents.
3. To analyse the extent to which quarry mining practices comply with environmental regulations and standards set by ZEMA and international guidelines.

1.4 Conceptual Framework

Recent studies continue to test the EKC hypothesis, which posits that environmental degradation initially rises with economic growth but declines after reaching a certain income threshold (Azam *et al*., 2024; Bettarelli *et al*., 2025) [2, 4]. Empirical evidence suggests that while the inverted U-shaped relationship holds in some contexts, its universality is contested, especially in developing regions where weak governance and limited enforcement hinder environmental improvements (Tang *et al*., 2025; Wang *et al*., 2024) [53, 63]. In the context of quarry mining in Kalengwa, this implies the area may be on the upward slope of the curve, where rapid extraction for economic gain occurs at the expense of environmental sustainability. Over time, stricter environmental regulations and green technologies could flatten the curve, reducing ecological harm (Bettarelli, *et al*., 2025) [4]. The SLA provides a human-centered framework for understanding how households derive livelihoods from available resources while coping with shocks and maintaining long-term sustainability. Recent research emphasizes its relevance in mining contexts, highlighting the need to integrate livelihood assets, institutional arrangements, and vulnerability factors to achieve sustainable outcomes (Delgado Jiménez, 2023; Nath & Parameswar, 2025) [11, 40]. Quarry mining in Kalengwa creates income opportunities but simultaneously undermines sustainability through land degradation, water contamination, and health risks. Operationalizing SLA in mining communities can guide interventions that balance resource extraction with social equity and resilience (Okyere, 2025) [44]. While EKC explains macro-level economic–environment trade-offs, SLA addresses micro-level livelihood dynamics. Together, they offer a robust theoretical foundation for analyzing quarry mining's dual impacts. However, EKC has been criticized for assuming universal improvement in environmental performance, overlooking governance failures and inequality in resource-dependent economies (Tang *et al*., 2025) [53]. SLA, by contrast, emphasizes context-specific strategies, making it particularly relevant for rural Zambia. This study adopts a dual-theoretical orientation, combining EKC's insights on economic growth and environmental thresholds with SLA's focus on household resilience and social equity. This integrated approach supports evidence-based recommendations for sustainable quarrying practices that balance development with environmental protection and community well-being.

1.5 Theoretical Framework

Environmental Kuznets Curve (EKC), points an inverted-U relationship between environmental degradation and economic growth; evidence is mixed and context-specific, especially where governance/enforcement are weak (Azam *et al*., 2024; Bettarelli *et al*., 2025; Tang *et al*., 2025; Wang *et al*., 2024) [2, 4, 53, 63].

Sustainable Livelihoods Approach (SLA), foregrounds household assets, institutions, and vulnerabilities, explaining how cash incomes from quarry work can coincide with exposure to environmental risks (Delgado Jiménez, 2023; Nath & Parameswar, 2025; Okyere, 2025) [11, 40, 44].

Complementarity and critiques. EKC offers macro-dynamics; SLA reveals micro-level vulnerability. EKC's assumption of eventual improvement is criticized for overlooking governance failures and inequities (Tang *et al*., 2025) [53]. The study integrates both to interpret Kalengwa.

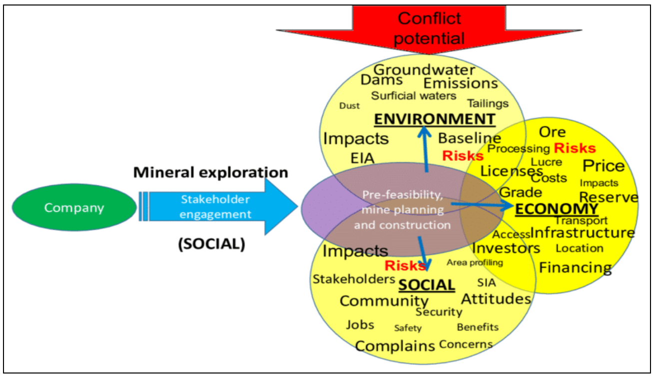

Fig 1: Conceptual Diagram Showing Mining and Environmental, Economic and Social Effects

1.6 Historical Context

From antiquity to the colonial era, quarrying underpinned infrastructure, shifting from artisanal to mechanized extraction. In Zambia, colonial and post-independence quarrying supported urbanization but oversight remained uneven; in Kalengwa, mechanization intensified dust, land degradation, and biodiversity loss (Lee, *et al*., 2024 [30]; Khalkho, 2025 [26]; PcW, 2024 [45]; Saleem & Ayalew, 2025 [49]; World Bank, 2025).

2. Literature Review

2.1 Overview

This chapter critically examines existing research on quarry mining, focusing on environmental impacts, socio-economic implications, and policy frameworks. It situates the present study within global, regional (African), and national (Zambian) contexts and identifies unresolved gaps that justify empirical work in Kalengwa. While quarry mining is widely studied, most literature emphasizes large-scale mining or general environmental issues; community-level effects in rural areas like Kalengwa remain under-documented. The dual nature of quarrying is evident: it supports infrastructure and employment while contributing to ecological degradation, pollution, and health risks. In Zambia, scholarship has largely focused on copper mining, leaving quarrying underexplored despite its growth. (Hilson & McQuilken, 2014; Ogba-Amaugo *et al*., 2020) [20, 42].

2.2 Global Overview of Quarry Mining

Aggregate extraction is vast and rising with urbanization; environmental costs include habitat destruction, erosion, air pollution, and water contamination. Dust emissions often exceed WHO thresholds; biodiversity loss and abandoned-quarry scarring persist. Sustainability measures (dust suppression, water recycling, rehabilitation) show uneven uptake in developing contexts (UNEP, 2020; Lee *et al*., 2024; Khalkho, 2025; Ogba-Amaugo *et al*., 2025; Teku, 2025; Okyere, 2025; Live to Plant, 2025) [60, 30, 26, 43, 44, 32].

2.3 National Context (Zambia)

Despite statutory frameworks (Mines and Minerals Development Act 2015; The Minerals Regulation Commission Act of 2024, Amendment), compliance is uneven; studies report elevated dust exposure and respirable silica in artisanal/small-scale quarries, associated with respiratory symptoms. Benefits are uneven and offset by land use loss and environmental health burdens (Tembo, 2020; Muneku & Naidoo, 2015; Mutambo & Munchini, 2019; U. S. Geological Survey, 2019; Tembo, 2020) [55, 37, 38, 58, 55].

2.4 Local Context (Kalengwa)

Kalengwa blends subsistence agriculture with expanding quarry operations. Reported impacts include farmland productivity declines, dust/noise health risks, sedimentation, and habitat fragmentation. Perceived deficits in compensation/consultation and limited district-level enforcement under the Environmental Management Act No. 12 of 2011 contribute to socio-environmental disparities (Hilson & McQuilken, 2014 [20]; Choudhury, *et al*., 2018; Government of the Republic of Zambia (GRZ), 2011 [17]; Phiri & Tembo, 2020 [46]).

2.5 Environmental Effects of Quarry Mining

Vegetation/topsoil removal accelerates erosion; quarry dust elevates PM10/PM2.5 and reduces plant photosynthesis; runoff adds sediments/metals; blasting noise/vibration disturb communities; biodiversity declines via habitat loss/fragmentation (Ogba-Amaugo, *et al*., 2020 [42]; Torahi *et al*., 2021 [56]; Mahmoodi, 2025 [34]; Hugo, 2024; Feher *et al*., 2021 [15]., 2024; Bektašević and Gutić, 2025; Nakade and Dhadse, 2024 [39]; Fois *et al*., 2025 [16]).

2.6 Research Gap

Community-level impacts quantified with scientific measurements and integrated with social indicators are scarce in Zambia's Northwestern Province; district-scale enforcement effectiveness is under-examined, justifying the mixed-methods approach in Kalengwa (Kitolea *et al*., 2025 [27]; Van Wyk & Haagner, 2025 [62]; ZEMA, 2019).

3. Research Methodology

3.1 Overview

The study uses a mixed-methods design to ensure objective, verifiable findings, combining quantitative environmental indicators and socio-economic surveys/interviews (Creswell, 2018; Enwin & Ikiriko, 2023; Lave & Lane, 2025; Kothari, 2014; Noble & Smith, 2025) [9, 12, 29, 28, 41].

3.2 Research Design
A descriptive and analytical cross-sectional design captured current conditions and enabled analysis of relationships between quarrying and observed impacts (Hunziker & Blankenagel, 2024; Lotfata *et al*., 2023; Babbie, 2020; Woodcock *et al*., 2025; Piet *et al*., 2021; Lee, 2025) [21, 33, 3, 66, 47, 31].

3.3 Study Area Description
Kalengwa (North-Western Province) has significant quarry materials (Precambrian basement complex rocks), tropical savannah climate (~1,200 mm), erosion/sedimentation concerns, and mixed livelihoods (Chileshe *et al*., 2024; Kitolea *et al*., 2025 [27]).

3.4 Target Population
Residents within 5 km of active sites (households, workers, businesses, leaders) plus institutional stakeholders; estimated 500 (out of a total population of 3500) directly interact with quarrying (CSO, 2010; ZSA, 2023; Ogba-Amaugo *et al*., 2025; Touray *et al*., 2025) [10, 72, 43, 57].

3.5 Sample Size and Sampling Techniques
Using Yamane (1967) [67] with N=500, e=0.1 gave n=83.33; rounded to 100 for representativeness. Stratified random sampling (workers/households/business/leaders) and purposive key informants (Etikan & Bala, 2017; Israel, 2021; Taherdoost, 2017) [13, 24, 51].

$$n = \frac{N}{1 + N(e)^2}$$

Where:
- n = Sample Size
- N = Known Target total Population (500)
- e = Marginal error 10%(0.1)

$$n = \frac{500}{1 + (500)(0.1)^2}$$

$$n = \frac{500}{(1+5)}$$

$$n = \frac{500}{(6)}$$

$$n = 83.33$$

The calculated sample size was 83 respondents. To enhance representativeness and account for non-response, the sample was rounded up to the nearest hundred to 100 respondents, which is statistically adequate for quantitative analysis in exploratory studies (Israel, 2021; Taherdoost, 2017) [24, 51]. Rounding up improves subgroup representation and aligns with recommendations for small populations where oversampling mitigates attrition risks. This sample size supports the study objectives by enabling meaningful descriptive and inferential analysis of socio-economic and environmental impacts.

3.6 Data Collection Methods
Primary: Air (PM10, PM2.5; WHO/USEPA), water (turbidity, pH, DO, metals, TPH; (ZABS 2022) [69], noise (ISO 1996) [23], biodiversity/land observations, socio-economic questionnaires/interviews (Creswell & Creswell, 2018; WHO, 2017 [64]; USEPA, 2023).
Secondary: ZEMA, CSO, Ministry of Mines, peer-reviewed sources (Yin, 2018; Noble & Smith, 2025) [68, 41].

3.7 Reliability and Validity
Instrument calibration, repeated measures, pilot testing (20 respondents), APHA protocols, construct/content validity checks; triangulation across environmental, survey, and documentary evidence (APHA, 2017; Cohen, Manion, & Morrison, 2018) [1, 8].

3.8 Data Analysis Techniques
SPSS (v26) for descriptive/inferential stats (χ^2, regression); environmental analytics per ZABS/WHO; GIS for spatial mapping; thematic analysis for interviews (Piet *et al*., 2021 [47]; Woodcock *et al*., 2025 [66]; Goodchild, 2018; Miles *et al*., 2019 [36]).

3.9 Ethical Considerations
ICU ethical clearance; district/community permissions; informed consent; confidentiality; non-intrusive environmental sampling (Resnik, 2020) [48].

3.10 Limitations in Methodology
Cross-sectional snapshot misses seasonal variability; 100-respondent sample may under-represent subgroups; instrument time-window limits cumulative exposure; budget limited water parameters; self-report bias mitigated via triangulation; generalizability cautioned (Hunziker & Blankenagel, 2024 [21]; Taherdoost, 2017 [51]; Woodcock *et al*., 2025 [66]; Noble & Smith, 2025 [41]; Creamer *et al*., 2025).

4. Results / Findings
4.1 Air Quality
PM10=180 µg/m³; PM2.5=85 µg/m³ (exceed WHO/ZEMA); TVOC=0.041 mg/m³ (within limits). Symptoms (cough, chest pain, eye irritation) align with elevated particulates (WHO, 2016; ZEMA, 2022) [65, 71].

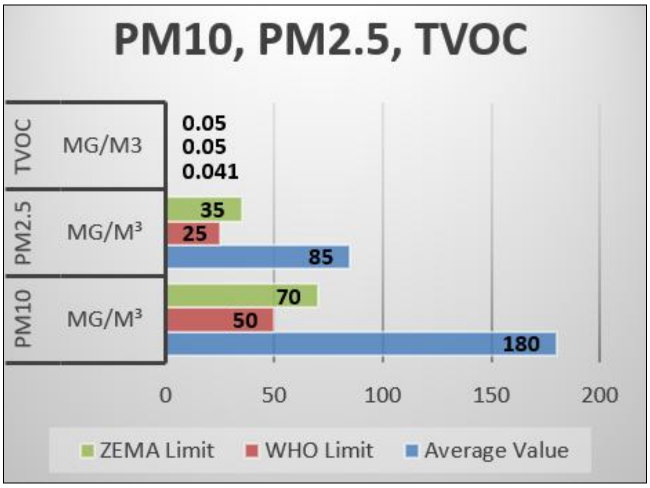

Fig 2: Air Quality Comparison (Measured vs Standards)

4.2 Noise
92 dB (blasting), 88 dB (crushing), 80 dB (haul roads), 68 dB (nearby village); exceed residential and often industrial thresholds; interview evidence of sleep disturbance, headaches, irritability (WHO, 2016; ZEMA, 2022) [65, 71].

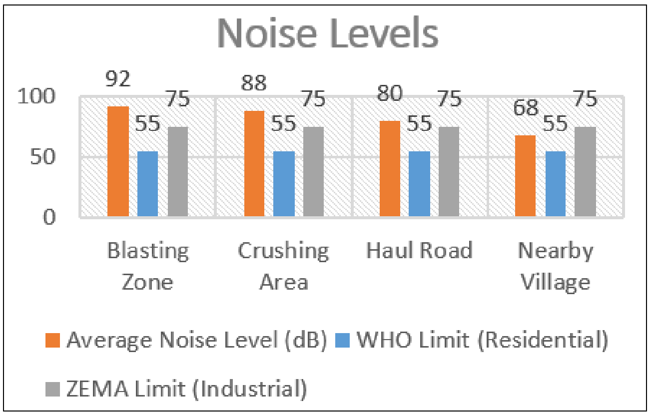

Fig 3: Noise Levels Comparison (Measured vs Standards)

4.3 Water Quality

Turbidity ~9 NTU; pH 6.1–6.5; DO ~4.2 mg/L. Chemical anomalies: Mg 110 mg/L, Se 50 ppb, Sb ~10 ppb; TPH 21 mg/L at one borehole (~1,300 m), linked to recent pump repair; no faecal coliforms (WHO, 2017 [64]; FAO/WHO, 2004 [14]; USEPA, 2023).

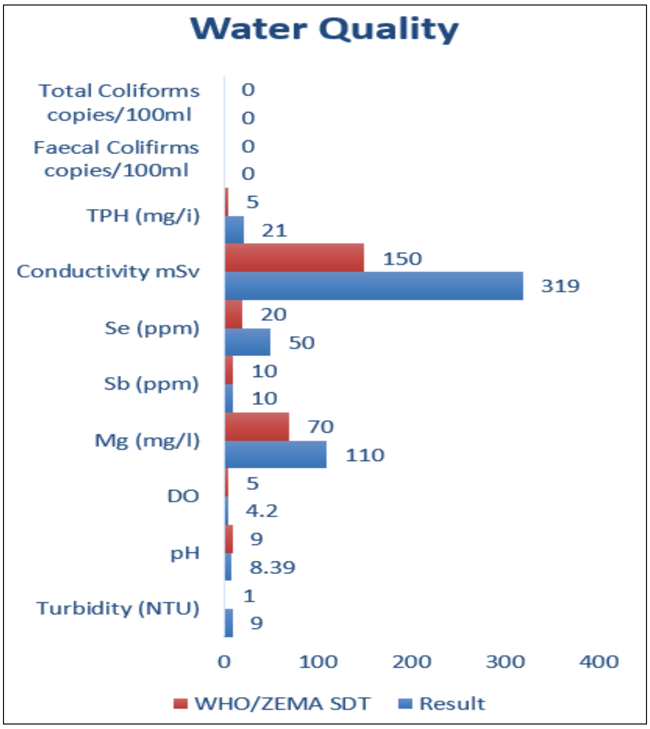

Fig 4: Water Quality Measurements

4.4 Biodiversity/Land

Wildlife present (antelopes, birds, small mammals); localized vegetation disturbance near access roads and altered landforms (pits/tailings); rehabilitation planning required.

4.5 Compliance Snapshot

Air particulates: non-compliance; noise: exceedances; water: localized anomalies and one TPH exceedance; tailings unlined; storm-water dams absent, priority compliance levers (WHO, 2016 [65]; ZEMA, 2022 [71]; WHO, 2017 [64]; USEPA, 2023).

5. Discussion

Particulate exceedances and symptom reports mirror regional quarry studies (Choudhurry *et al.*, 2018; Ogba-Amaugo, *et al.*, 2020 [42]; Touray *et al.*, 2025 [57]). Noise profiles imply potential auditory/stress risks (Feher *et al.*, 2021; Merijanti & Lie, 2022) [15, 35]. Water shows sediment loading and localized chemistry/TPH anomalies; interpretation follows WHO/FAO-WHO/USEPA guidance (WHO, 2017 [64]; FAO/WHO, 2004 [14]; USEPA, 2023). Habitat fragmentation and landform alteration persist without rehabilitation (Nakade and Dhadse, 2024; Fois *et al.*, 2025) [39, 16]. Livelihood gains are tempered by precarious work and health costs; gendered patterns reinforce inequity (Hilson & McQuilken, 2014 [20]; Yu *et al.*, 2024). Governance gaps—weak enforcement, monitoring deficits, unlined tailings—explain non-compliance (ZEMA, 2019; Phiri & Tembo, 2020 [46]). EKC suggests Kalengwa is on the ascending slope; SLA explains household-level vulnerability and mixed perceptions (Azam *et al.*, 2024; Bettarelli *et al.*, 2025; Wang *et al.*, 2024; Delgado Jiménez, 2023; Nath & Parameswar, 2025) [2, 4, 63, 11, 40].

6. Conclusion

Quarry mining in Kalengwa provides short-term economic benefits while compromising environmental quality and public health. Elevated PM10/PM2.5 and noise levels exceed benchmarks; water shows high turbidity and localized chemical/TPH spikes; land and habitat are fragmented near operations. Health symptoms, reduced crop performance, and increased medical expenditures attenuate net gains. Without targeted dust/noise control, water protection (lined tailings, runoff dams), progressive rehabilitation, and stronger enforcement/engagement, long-term ecological degradation, health risks, and livelihood insecurity will persist (WHO, 2016 [65]; ZEMA, 2022 [71]; ZEMA, 2019).

7. Recommendations

Policy and Governance

Strengthen enforcement (EIA, audits, sanctions), decentralize monitoring capacity/resources, embed social safeguards (transparent land acquisition, compensation, gender-inclusive hiring, grievance redress) (ZEMA, 2019; Phiri & Tembo, 2020 [46]; UN, 2015 [59]; Tembo, 2020 [55]).

Community-Based Strategies

Participatory land-use planning, community-led restoration (tree planting, erosion control, pit fencing/backfilling), alternative livelihoods (agroforestry, small enterprises), risk communication on dust, noise and safe water (GRZ, 2011 [17]; ZEMA, 2019; Hilson & McQuilken, 2014 [20]; WHO, 2016 [65]; WHO, 2017 [64]).

Sustainable Quarrying Practices

Dust suppression (water spraying, speed limits, vegetative windbreaks), acoustic controls (enclosures/barriers), daytime blasting; impermeable liners and storm-water retention; water recycling and routine effluent testing; PPE, toolbox talks, audiometric/respiratory surveillance (IFC, 2023; WHO, 2017; ZEMA, 2022; WHO, 2016) [22, 64, 71, 65].

Stakeholder Engagement

Multi-stakeholder platforms for co-monitoring and public compliance reports; align CSR with local priorities (clinics, water infrastructure, roads) (ZEMA, 2019; IFC, 2023 [22]; Tembo, 2020 [55]; UN, 2015 [59]).

Further Research

Longitudinal monitoring across seasons; expanded water chemistry/groundwater modelling; gender-disaggregated and vulnerability analysis; comparative compliance studies (WHO, 2017 [64]; ZEMA, 2019; Hilson & McQuilken, 2014 [20]; Yu *et al*., 2024; IFC, 2023 [22]; Phiri & Tembo, 2020 [46]).

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